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Investigation des fonctions du corps calleux par l'étude du transfert interhémisphérique de l'information visuelle et motrice chez les individus normaux et callosotomisés

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Cette thèse intitulée :
Investigation des fonctions du corps calleux par l'étude du transfert interhémisphérique de l'information visuelle et motrice chez les individus normaux et callosotomisés

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RÉSUMÉ

Le principal rôle du corps calleux est d'assurer le transfert de l'information entre les hémisphères cérébraux. Du support empirique pour cette fonction provient d'études investiguant la communication interhémisphérique chez les individus à cerveau divisé (ICD). Des paradigmes expérimentaux exigeant une intégration interhémisphérique de l'information permettent de documenter certains signes de déconnexion calleuse chez ces individus. La présente thèse a investigué le transfert de l'information sous-tendant les phénomènes de gain de redondance (GR), de différence croisé– non-croisé (DCNC) et d'asynchronie bimanuelle chez les ICD et les individus normaux, et a ainsi contribué à préciser le rôle du corps calleux.

Une première étude a comparé le GR des individus normaux et des ICD ayant subi une section partielle ou totale du corps calleux. Dans une tâche de détection, le GR consiste en la réduction des temps de réaction (TR) lorsque deux stimuli sont présentés plutôt qu'un seul. Typiquement, les ICD présentent un GR beaucoup plus grand (supra-GR) que celui des individus normaux (Reuter-Lorenz, Nozawa, Gazzaniga, & Hughes, 1995). Afin d'investiguer les conditions d'occurrence du supra-GR, nous avons évalué le GR en présentation interhémisphérique, intrahémisphérique et sur le méridien vertical, ainsi qu'avec des stimuli requérant une contribution corticale différente (luminance, couleur équiluminante ou mouvement). La présence d'un supra-GR chez les ICD partiels et totaux en comparaison avec celui des individus normaux a été confirmée. Ceci suggère qu'une section antérieure du corps calleux, qui perturbe le transfert d'informations de nature

motrice/décisionnelle, est suffisante pour produire un supra-GR chez les ICD. Nos données permettent aussi d'affirmer que, contrairement au GR des individus normaux, celui des ICD totaux est sensible aux manipulations sensorielles. Nous concluons donc que le supra-GR des ICD est à la fois attribuable à des contributions sensorielles et motrices/décisionnelles.

Une deuxième étude a investigué la DCNC et l'asynchronie bimanuelle chez les ICD et les individus normaux. La DCNC réfère à la soustraction des TR empruntant une voie anatomique « non-croisée » aux TR empruntant une voie anatomique « croisée », fournissant ainsi une estimation du temps de transfert interhémisphérique. Dans le contexte de notre étude, l'asynchronie bimanuelle réfère à la différence de TR entre la main gauche et la main droite, sans égard à l'hémichamp de présentation. Les effets de manipulations sensorielles et attentionnelles ont été évalués pour les deux mesures. Cette étude a permis d'établir une dissociation entre la DCNC et l'asynchronie bimanuelle. Précisément, les ICD totaux, mais non les ICD partiels, ont montré une DCNC significativement plus grande que celle des individus normaux, alors que les deux groupes d'ICD se sont montrés plus asynchrones que les individus normaux. Nous postulons donc que des processus indépendants sous-tendent la DCNC et la synchronie bimanuelle. De plus, en raison de la modulation parallèle du GR et de l'asynchronie bimanuelle entre les groupes, nous suggérons qu'un processus conjoint sous-tend ces deux mesures.

Mots clé : Corps calleux, transfert interhémisphérique, gain de redondance, différence croisé– non-croisé, asynchronie, coordination bimanuelle, cerveau divisé, callosotomie.

ABSTRACT

The main role of the corpus callosum is the transfer of information across the cerebral hemispheres. Evidence for this function comes from studies investigating the interhemispheric communication of split-brain individuals. Specific experimental paradigms requiring interhemispheric integration have enabled the documentation of disconnection symptoms for split-brain individuals. Along those lines, the present thesis investigated the transfer of information underlying the redundant target effect (RTE), the crossed-uncrossed difference (CUD), and bimanual asynchrony of normal and split-brain individuals, and therefore contributed to further our knowledge of the role of the corpus callosum.

The first study investigated the RTE of partial split-brain (anterior section), total split-brain, and normal individuals. The RTE occurs when reaction times (RTs) to multiple stimuli are faster than RTs to a single stimulus. Split-brain individuals typically exhibit an enhanced RTE as compared to normal individuals (Reuter-Lorenz et al., 1995). In order to investigate the conditions in which the enhanced RTE occurs, we tested the RTE in interhemispheric, intrahemispheric, and midline conditions, as well as with stimuli requiring different cortical contributions (stimuli defined by luminance, equiluminant colour, or motion). Our data supported the occurrence of an enhanced RTE for partial and total split-brain individuals as compared to normal individuals. This suggests that an anterior section of the corpus callosum, which disrupts the transfer of motor/decisional information, suffices to produce an enhanced RTE in split-brain individuals. In addition, in contrast with the

RTE of normal individuals, that of total split-brain individuals was modulated as a function of a sensory manipulation. We therefore conclude that the enhanced RTE of split-brain individuals is attributable to both sensory and motor/decisional contributions.

The second study investigated the CUD and the bimanual asynchrony of normal, partial split-brain, and total split-brain individuals. The CUD refers to the subtraction of mean RTs of uncrossed hand-visual hemifield combination from mean RTs of crossed hand-visual hemifield combination. In the context of our study, the asynchrony reflected the difference between the left-hand RT and the right-hand RT on each trial, irrespective of the side of presentation. The effect of sensory and attentional manipulations was assessed for both measures. Our study contributed to dissociate the CUD and bimanual asynchrony. Specifically, total split-brain individuals, but not partial split-brain individuals, showed a larger CUD than normal individuals, whereas both split-brain groups were less synchronous than normal individuals. We therefore postulate that independent processes underlie the CUD and bimanual asynchrony. Furthermore, the parallel modulation of the RTE and bimanual asynchrony across groups suggest common underlying processes for these two measures.

Keywords : Corpus callosum, interhemispheric transfer, redundant target effect, redundancy gain, crossed-uncrossed difference, bimanual coordination, asynchrony, split-brain, callosotomy.

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LISTE DES ABRÉVIATIONS

CC	Corps calleux
Col	*Colour*
CUD	*Crossed-uncrossed difference*
DCNC	Différence croisé– non-croisé
DTI	*Diffusion tensor imaging*
fMRI	*Functional magnetic resonance imaging*
GR	Gain de redondance
HARDI	*High angular resolution diffusion imaging*
ICD	Individu à cerveau divisé
Inter	*Interhemispheric*
Intra	*Intrahemispheric*
IRM/MRI	Imagerie par résonance magnétique/*Magnetic resonance imaging*
ISI	*Inter-stimulus interval*
ITI	*Inter-trial interval*
Lum	*Luminance*
Lh	*Left hand*
LVF	*Left visual field*
ms	milliseconde / *millisecond*
Mid	*Midline*
Mot	*Motion*
Rh	*Right hand*
RTs	*Reaction times*

RTE	*Redundant target effect*
RVF	*Right visual field*
SB	*Split-brain*
TMS	*Transcranial magnetic stimulation*
TR	Temps de réaction

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INTRODUCTION GÉNÉRALE

BREF HISTORIQUE

L'épilepsie est un trouble neurologique caractérisé par des crises au cours desquelles se produit une activité synchrone excessive des neurones. De manière typique, un traitement pharmacologique est suffisant pour contrôler la survenue de ces crises. Or, dans une faible proportion de cas, l'épilepsie est réfractaire à la médication et exige le recours à des traitements alternatifs. La callosotomie, une chirurgie impliquant la section des fibres du corps calleux, représente l'une de ces alternatives. Le rationnel de cette chirurgie repose sur l'élimination du lien unissant les deux hémisphères cérébraux de manière à limiter la propagation de l'activité électrique lors d'une crise épileptique.

Le recours à la callosotomie a initialement été guidé par l'impressionnante étendue des fibres calleuses et par l'observation d'une diminution des crises épileptiques suite à une dégénérescence du corps calleux. En 1940, Van Wagenen et Herren ont été les pionniers dans l'utilisation de cette technique chirurgicale (Van Wagenen & Herren, 1940). Les premières sections ont effectivement eu pour effet de diminuer le nombre de crises épileptiques des patients. La logique voulant qu'une section du corps calleux interrompe non seulement le transfert de l'activité électrique épileptogène, mais aussi le transfert général d'informations, des perturbations générales du fonctionnement étaient attendues. Dans cette optique, Akelaitis (1945) a étudié une cohorte de patients callosotomisés, aussi appelés individus à cerveau divisé (ICD), sans pour autant réussir à identifier les signes de déconnexion

interhémisphérique aujourd'hui documentés. Plusieurs années se sont écoulées avant qu'une technique de présentation, prévenant l'activation simultanée des deux hémisphères cérébraux, soit introduite par Bogen et Vogel (1962) et permette d'identifier la présence de signes de déconnexion interhémisphérique chez l'humain (Bogen, Fisher, & Vogel, 1965). Ces signes se manifestent en regard du principe de spécialisation hémisphérique, c'est-à-dire un traitement prépondérant de certaines fonctions cognitives par un hémisphère spécifique. Ces études pionnières ont donc pavé la voie aux études portant sur le transfert interhémisphérique de l'information et sur la spécialisation hémisphérique.

LA CALLOSOTOMIE

La callosotomie est une procédure chirurgicale pouvant s'opérer en une ou deux étapes. Dans certains cas, une section partielle du corps calleux est suffisante pour diminuer significativement le nombre de crises. Le choix d'effectuer une section antérieure ou postérieure du corps calleux peut être guidé par l'information disponible quant au locus épileptique. Traditionnellement, une section antérieure est d'abord effectuée, et si la fréquence des crises persiste, la callosotomie peut être complétée par une section des fibres postérieures lors d'une seconde chirurgie.

Une section complète du corps calleux peut mener à l'inhibition des crises épileptiques par la désynchronisation de l'activité épileptogène. Néanmoins, cette activité peut parfois continuer à se propager via les commissures extra-calleuses, ce

qui rend les résultats de la callosotomie difficilement prédictibles. Spécifiquement, un arrêt complet des crises est rapporté dans seulement 5 à 10% des cas et n'écarte pas la possibilité d'un retour des crises au cours des années suivantes (Shorvon, 2005). Malgré tout, la fréquence et l'intensité des crises sont fréquemment diminuées suite à la chirurgie. À titre d'exemple, une étude portant sur une cohorte de 99 individus ayant subi une callosotomie entre 1989 et 1997 en Colombie suggère une cessation complète, ou une diminution notable du nombre de crises, chez 90% des patients au cours des 35 mois suivant la chirurgie (Fandino-Franky, Torres, Narino, & Fandino, 2000).

L'efficacité maximale de la callosotomie s'exerce dans un contexte de traitement de crises atoniques (crise avec chute) ou de crises tonico-cloniques généralisées secondaires (Rosenfeld & Roberts, 2009). À ce jour, cette chirurgie est encore utilisée, bien qu'il s'agisse d'un traitement de dernier recours et que son emploi soit en déclin au profit de traitements moins invasifs comme la stimulation du nerf vague. D'un point de vue neuropsychologique, l'étude des ICD offre une opportunité unique pour contribuer à l'avancement de notre compréhension des interactions hémisphériques et des échanges qui les sous-tendent. Dans ce contexte, la présente thèse s'attarde tout particulièrement à l'investigation du rôle de transfert interhémisphérique qu'assure le corps calleux.

L'ANATOMIE DU CORPS CALLEUX CHEZ L'HUMAIN

Le corps calleux se développe de manière intra-utérine à compter de la douzième semaine de vie et son développement se poursuit jusqu'à la 22^{ième} semaine (Achiron & Achiron, 2001). La portion rostrale du corps calleux se forme d'abord et le développement se poursuit caudalement, donnant lieu à la formation du tronc et du splénium (Rakic & Yakovlev, 1968). Chez certains fœtus, le développement de cette structure peut être perturbé, menant à une agénésie calleuse, soit une absence partielle ou totale du corps calleux. Des études d'autopsie suggèrent que l'agénésie calleuse se produit dans un cas sur 20 000 et peut se présenter de manière isolée ou être associée à d'autres pathologies (Burton, 2007).

Les différentes techniques utilisées pour estimer le nombre de fibres calleuses reliant les deux hémisphères cérébraux proposent des valeurs variant de 200 à 800 millions (Aboitiz, 1992; Koppel & Innocenti, 1983). Nonobstant la variabilité des estimations, le corps calleux constitue le plus important réseau d'interconnections du cerveau. Cette structure, illustrée dans la Figure 1A, se divise en quatre principales parties dont l'organisation rostro-caudale comprend respectivement le rostrum, le genou, le tronc et le splénium (Clarke, 2003a). Chacune de ces portions calleuses acheminent de l'information de nature différente telle que schématisée dans la Figure 1B. La portion antérieure du corps calleux relie les lobes frontaux et transfère l'information ayant trait aux fonctions cognitives de haut niveau, à l'attention sélective, à la mémoire procédurale, ainsi qu'aux fonctions pré-motrices et motrices

(Banich, 2003; Schmahmann & Deepak, 2006). La portion médiane du corps calleux, soit la portion postérieure du tronc, relie les lobes temporaux et pariétaux et transfère principalement l'information de nature somesthésique et auditive. La portion postérieure du corps calleux, le splénium, relie les lobes occipitaux et contribue au transfert de l'information visuelle. Cette organisation topographique du corps calleux est supportée par des études récentes recourant à différentes techniques d'imagerie de diffusion (Chao et al., 2009; Hofer & Frahm, 2006).

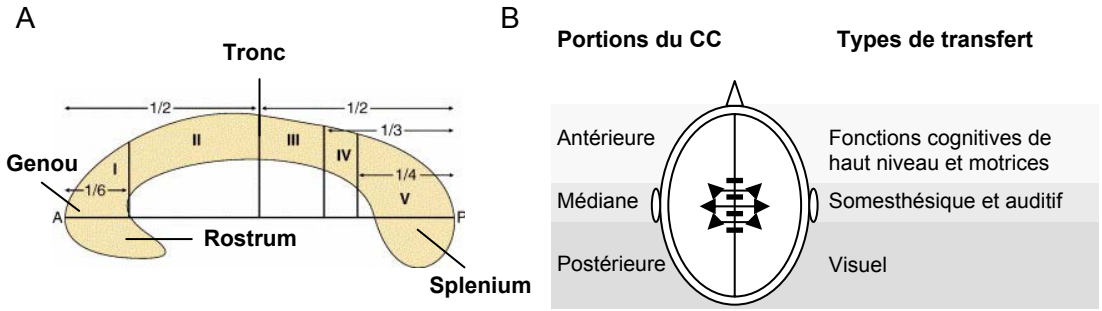

Figure 1. A : Topographie d'une coupe midsagitale du corps calleux (CC). Région I: préfrontal; région II: prémotrice et prémotrice supplémentaire; région III : motrice; région IV : sensorielle; région V : pariétale, temporale, et occipitale. (Figure adaptée de Hofer & Frahm, 2006, avec permission). B : Schéma des différentes portions du corps calleux associées au type d'informations dont elles assurent le transfert interhémisphérique.

Les fibres calleuses varient à l'égard de leur taille et de leur vitesse de transfert. La distribution spatiale se résume grossièrement à ce que les fibres de petit diamètre soient principalement concentrées dans la portion antérieure et dans le splénium, alors que les fibres de plus gros diamètre se concentrent dans le tronc. Étant donné qu'une relation directe existe entre la vélocité de conduction électrique et le diamètre

des fibres nerveuses, les fibres donnant lieu au transfert le plus rapide se retrouvent dans la portion calleuse dédiée à transmettre l'information somatosensorielle (Aboitiz, Lopez, & Montiel, 2003).

Les connexions dédiées au transfert interhémisphérique présentent une organisation homo- ou hétérotopique (Clarke, 2003b). Les connexions homotopiques relient des portions corticales anatomiquement et fonctionnellement équivalentes. Quant à elles, les connexions hétérotopiques relient des portions corticales anatomiquement et fonctionnellement différentes.

LES STRUCTURES ALTERNATIVES IMPLIQUÉES DANS LE TRANSFERT INTERHÉMISPHÉRIQUE

Bien que le corps calleux soit la principale structure impliquée dans le transfert interhémisphérique de l'information, d'autres commissures sont aussi candidates pour desservir cette fonction.

La commissure antérieure connecte les régions corticales antérieures temporales incluant les aires olfactives (Cook, 1986). Chez l'homme, sa taille représente approximativement 1/50^{e} de la taille du corps calleux et contribue au transfert interhémisphérique de manière relativement mineure (Cook, 1986). Chez le singe, en absence du corps calleux, la commissure antérieure assurerait un transfert d'informations visuelles suffisant à la discrimination de couleurs, de formes et

d'orientations (Butler, 1979). Son importance fonctionnelle reste toutefois nébuleuse chez l'humain.

La commissure postérieure est composée de fibres blanches qui traversent la ligne médiane dorsalement à l'aqueduc cérébral. Les fonctions précises de cette commissure ne sont pas bien connues. Toutefois, sur la base d'études montrant une absence d'effet suite à une section de la commissure postérieure chez le chat chiasmatomisé, il semblerait que le rôle de cette commissure, de même que celui de la commissure intertectale, soit tout au plus secondaire dans le transfert interhémisphérique de l'information (Berlucchi, Buchtel, & Lepore, 1978).

La commissure intercolliculaire représente un ensemble d'axones reliant les deux collicules supérieurs. Chez l'homme, l'organisation fonctionnelle des collicules supérieurs et de leurs voies intercolliculaires est peu connue. Il est supposé qu'un transfert d'informations visuelles s'y opère, sans toutefois que la nature de l'information qui y transfère soit précisément identifiée (Tardif & Clarke, 2002). En plus d'assurer la transmission de certaines informations visuelles et non-visuelles, les collicules supérieurs seraient aussi impliqués dans le contrôle des mouvements oculaires. Précisément, les couches colliculaires profondes seraient possiblement impliquées dans le traitement visuel d'aspects complexes incluant l'attention (Tardif & Clarke, 2002).

Finalement, la commissure hippocampique traverse la ligne médiane sous la portion rostrale du splénium. L'organisation fonctionnelle du cortex suggère que son rôle serait dédié au transfert d'informations liées à l'apprentissage déclaratif et à la mémoire puisque cette commissure relie certaines structures des lobes temporaux médians (Schmahmann & Deepak, 2006).

LE SYSTÈME VISUEL

Un bref survol de certaines propriétés du système visuel s'impose pour bien comprendre les effets des différentes manipulations utilisées dans les études abordées au cours des prochaines sections. Spécifiquement, l'organisation croisée du système visuel et les différentes voies de traitement visuel fournissent différents moyens d'évaluer le rôle du corps calleux dans le transfert de l'information visuelle.

L'ORGANISATION CROISÉE

L'anatomie croisée du système visuel est qualifiée ainsi en raison des axones des hémirétines nasales de chaque œil qui croisent la ligne médiane (décussation) et projettent au corps genouillé latéral et à l'hémisphère opposé (Bear, Connors, & Paradiso, 2007). En raison de cette architecture, une section du chiasma optique peut empêcher l'information visuelle de parvenir à l'hémisphère controlatéral à la présentation. Dans un tel cas, l'information visuelle projetée à un hémichamp est

d'abord accessible à un seul hémisphère et peut rapidement traverser la ligne médiane seulement si le corps calleux permet un échange cortical.

Si le chiasma optique est intact et que le corps calleux est sectionné, il est aussi possible de confiner le traitement d'un stimulus visuel à un seul hémisphère. Pour ce faire, une présentation tachistoscopique en champ visuel divisé peut être utilisée. Cela consiste en la présentation brève des stimuli dans le champ visuel droit et/ou gauche. En raison de la décussation partielle du système visuel, un stimulus latéralisé est alors uniquement représenté dans l'hémisphère controlatéral à sa présentation. L'utilisation de la technique tachistoscopique chez les ICD permet donc de stimuler un seul hémisphère cérébral.

LES SYSTÈMES PARVOCELLULAIRE ET MAGNOCELLULAIRE

Les différents types d'informations visuelles acheminés de la rétine vers le cortex transitent en parallèle par l'intermédiaire des systèmes magnocellulaire et parvocellulaire. Ces deux systèmes projettent à des aires corticales différentes. Le système magnocellulaire projette par la voie dorsale dans le cortex pariétal et le système parvocellulaire projette par la voie ventrale dans le cortex temporal inférieur (Underleider & Mishkin, 1982). Le système magnocellulaire, aveugle aux couleurs, répond préférentiellement au changement de luminance et au mouvement (Chapman, Hoag, & Giaschi, 2004). Au contraire, le système parvocellulaire est particulièrement sensible aux oppositions de couleurs (Schiller & Logothetis, 1990).

Quant aux neurones des collicules supérieurs, qui reçoivent principalement des afférences du système magnocellulaire, ils n'ont pas de propriétés leur permettant de distinguer l'opposition entre les couleurs (Marrocco & Li, 1977). La logique sous-tendant l'organisation des différents systèmes de traitement visuel sera utile pour comprendre les manipulations introduites dans certaines études exploitant cette caractéristique du système visuel.

LE TRANSFERT INTERHÉMISPHÉRIQUE DE L'INFORMATION

RECHERCHE ANIMALE

Des avancées significatives dans la compréhension des fonctions de transfert du corps calleux ont été réalisées grâce à la recherche animale. Entre autres, des études ont évalué les capacités de transfert d'apprentissage chez le chat ayant subi une section du chiasma optique. Tel qu'exposé précédemment, cette manipulation a pour effet de limiter les entrées visuelles à un seul hémisphère. Dans ce contexte, malgré l'occlusion d'un œil chez un chat chiasmatomisé, l'apprentissage de discrimination de formes s'est montré transférable de l'œil entraîné à l'œil occlus grâce à la libre communication de l'information entre les deux hémisphères (Myers, 1955). Toutefois, un chat ayant subi une section du chiasma optique et du corps calleux n'a pas montré un tel transfert d'apprentissage. Au contraire, l'œil occlus a dû réapprendre la tâche complètement, ne bénéficiant aucunement de l'apprentissage initial effectué par l'œil entraîné.

Des études utilisant l'enregistrement électrophysiologique unicellulaire chez l'animal ont aussi montré que le corps calleux joue un rôle déterminant dans l'intégration de l'information présentée sur le méridien vertical, c'est-à-dire la ligne imaginaire séparant verticalement les champs visuels (Lepore, Ptito, & Guillemot, 1986). Chez le chat, l'élaboration de cette hypothèse s'est appuyée sur l'organisation des neurones calleux dont un grand nombre est situé sur la bordure des aires visuelles 17/18 de Brodmann et dont les champs récepteurs de certains sont bilatéraux, chevauchant ainsi la scissure interhémisphérique (Innocenti, 1980; Lepore & Guillemot, 1982). Cette organisation fait en sorte que la portion centrale du champ visuel est représentée dans chaque hémisphère, assurant ainsi une fusion médiane et permettant une perception unitaire de l'espace visuel. Cette propriété calleuse d'unification des expériences semble se généraliser aux systèmes somatosensoriels et auditifs (Iwamura, 2000; Manzoni, Barabresi, Conti, & Fabri, 1989; Ptito, 2003). Il a donc été suggéré que le corps calleux assure un rôle d'unification des expériences perceptives (Lepore, 1995).

RECHERCHE CHEZ L'HUMAIN

L'investigation des fonctions du corps calleux a aussi largement bénéficié de la recherche effectuée auprès d'ICD. L'utilisation de différentes tâches comportementales auprès de ces patients a permis d'élaborer une compréhension anatomique du transfert de l'information pour différentes fonctions sensorielles et

cognitives. Les sections suivantes font état des connaissances actuelles dans le domaine du transfert interhémisphérique de l'information visuo-motrice chez les ICD. Tout d'abord, la performance générale de ces individus à des tâches exigeant une intégration interhémisphérique est brièvement présentée. Ensuite, des études portant sur le GR, la DCNC et l'asynchronie bimanuelle sont exposées dans le but de mettre en lumière la capacité, ou l'incapacité, des hémisphères cérébraux à coopérer en l'absence du corps calleux.

Études portant sur l'intégration interhémisphérique

La callosotomie déconnecte les hémisphères au niveau cortical et les prive ainsi de la principale voie d'échanges interhémisphériques. Le syndrome de déconnection résulte donc en un fonctionnement isolé de chaque hémisphère cérébral (Sperry, 1986). Or, certaines tâches nécessitent que les hémisphères travaillent de concert et mettent en commun des informations dont l'accès est disponible à un seul d'entre eux. De telles tâches s'avèrent particulièrement informatives quant à la façon dont les informations peuvent être intégrées de manière interhémisphérique en l'absence du corps calleux. Aussi, il s'avère parfois utile de comparer la performance de patients ayant subi différentes sections du corps calleux afin d'identifier la distribution fonctionnelle à travers cette structure.

Une investigation de la nature des informations résiduelles transférant d'un hémisphère à l'autre suite à une section calleuse a été menée. Certains auteurs ont

suggéré qu'une intégration d'informations visuo-spatiales et cognitives de haut niveau peut s'effectuer chez des individus callosotomisés. Un appui en faveur de cette position provient d'une étude portant sur deux patients commissurotomisés (ayant subi une section du corps calleux, des commissures antérieure et hippocampique) qui ont réussi à juger de la position relative des stimuli dans une tâche exigeant l'intégration d'informations entre les champs visuels (Sergent, 1987). De plus, des résultats similaires ont été obtenus avec des tâches reposant sur des capacités de décision lexicale, sur un jugement d'orientation spatiale de même que sur des habiletés de calcul. À la lumière de ces informations, il a été postulé qu'un échange extra-calleux prend place pour assurer le transfert d'informations. De telles données ont supporté l'idée selon laquelle des voies sous-corticales peuvent agir en tant que voie alternative dans le transfert de l'information interhémisphérique (Holtzman, 1984).

Les études ne s'accordent toutefois pas quant à la nature et à la complexité des informations pouvant être acheminées par les voies sous-corticales. À titre d'exemple, J.W., un patient ayant subi une section du corps calleux et de la commissure hippocampique, a été soumis à une tâche de discrimination en choix forcés qui consistait à déterminer si un stimulus présenté dans l'hémichamp gauche était identique ou différent à un stimulus simultanément présenté dans l'hémichamp droit (Tramo et al., 1995). Les stimuli pouvaient varier en fonction de leur orientation, leur forme, leur luminance ou leur position relative. Les performances de J.W. à cette tâche se sont situées au niveau du hasard pour les discriminations impliquant l'orientation, la forme et la luminance, et tout juste au-dessus du niveau

de chance pour les discriminations s'appuyant sur la position relative, mettant ainsi en doute l'efficacité des voies sous-corticales à transférer certains types d'informations.

Le gain de redondance

Le paradigme de GR s'est avéré particulièrement utile pour d'investiguer les effets d'une section du corps calleux sur le transfert interhémisphérique de l'information. La tâche de GR consiste en la détection de stimuli simples et redondants. En moyenne, les temps de réponse sont plus rapides lorsque deux cibles sont présentées plutôt qu'une seule. La différence de temps entre ces deux conditions reflète un effet de facilitation (TR plus rapides) dans la détection des stimuli redondants, phénomène désigné sous le nom de GR. Les patrons typiques de GR observés chez les individus normaux et callosotomisés sont illustrés dans la Figure 2.

L'effet de GR s'observe supposément lorsque les stimuli sont présentés bilatéralement plutôt que dans un seul champ visuel, activant ainsi les deux hémisphères cérébraux plutôt qu'un seul (Reuter-Lorenz et al., 1995). Chez les individus normaux, le GR est généralement de l'ordre de 10-15 ms (Miller, 1982). Chez les ICD, un GR beaucoup plus grand et variable que celui des individus normaux est observé, atteignant des valeurs jusqu'à 70–100 ms, qui toutefois varient considérablement entre les individus (Reuter-Lorenz et al., 1995; Roser & Corballis, 2002).

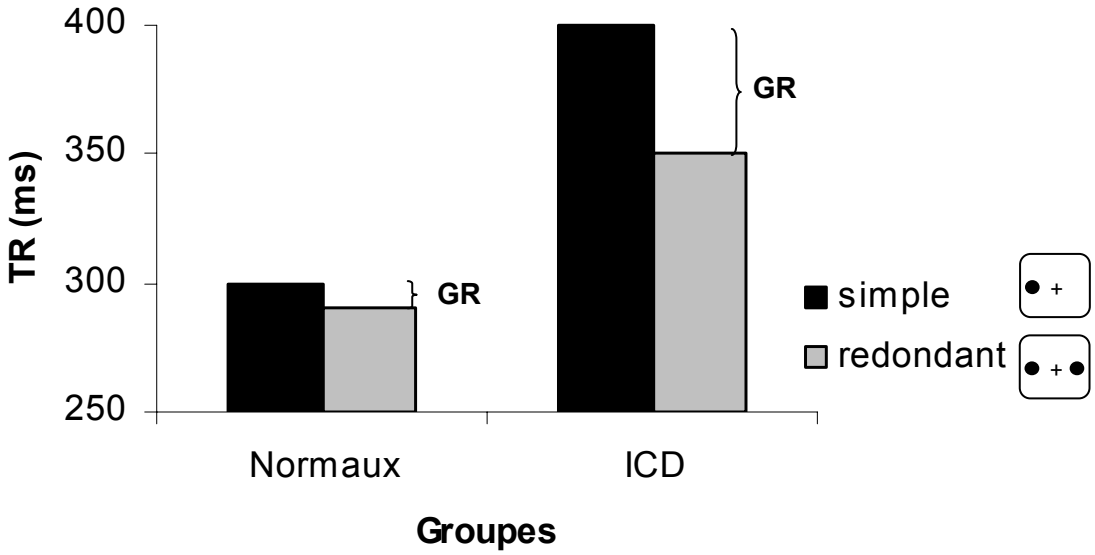

Figure 2. Illustration du GR typiquement obtenu chez les individus à cerveau divisé (ICD) et normaux. Dans les deux cas, le GR se manifeste par une diminution du temps de détection lorsque deux cibles sont présentées plutôt qu'une seule. Les ICD montrent un supra-GR en comparaison avec celui des individus normaux.

Chez les individus normaux, le GR reflète supposément une intégration rapide d'informations visuelles via le corps calleux qui favorise une coopération entre les hémisphères cérébraux. Or, chez les individus callosotomisés, un tel échange ne peut s'effectuer par la voie calleuse. La présence d'un supra-GR chez ces individus est donc paradoxale puisqu'elle suppose une interaction neurale entre deux hémisphères cérébraux déconnectés au niveau cortical.

Deux principales catégories de modèles ont tenté d'expliquer le phénomène de GR, notamment les modèles de course et les modèles de coactivation. L'hypothèse des modèles de course postule qu'il s'instaure une course entre des canaux de traitement

parallèles et indépendants pouvant chacun produire un signal suffisant au déclenchement de la réponse (Raab, 1962). Selon ce type de modèle, l'activation des différents canaux ne peut être combinée, écartant ainsi l'hypothèse d'une interaction neurale lors du traitement des stimuli. Le canal vainqueur de la course détermine le TR à un essai. En fonction des probabilités, une fois moyennés, les essais bilatéraux (qui activent directement deux hémisphères plutôt qu'un seul) produisent infailliblement des TR plus courts que les essais unilatéraux (qui n'activent qu'un seul hémisphère). Une équation d'inégalité permet d'évaluer si le GR excède la facilitation prédite par les modèles de course (Miller, 1982). Cette équation établie une limite au-delà de laquelle la facilitation produite par la redondance des stimuli ne suffit pas à expliquer l'amplitude du GR. Si cette limite est excédée, une explication complémentaire à celle de l'approche probabilistique doit justifier l'effet de redondance.

Les modèles de coactivation fournissent cette explication complémentaire. Ce type de modèles suppose que l'activation des différents canaux se combine pour participer à l'initiation de la réponse. Selon cette perspective, la réponse aux stimuli redondants est rapide puisque deux sources contribuent à l'atteinte d'un seul critère. À la différence des modèles de course, les différents canaux n'entament pas seulement une course mais combine plutôt leur activation, initiant par conséquent des TR plus rapides. Ces modèles fournissent donc une alternative pour comprendre l'effet de GR. Cette approche implique aussi l'existence d'un locus où se combine l'activation des différents canaux. Récemment, certaines études ont proposé que les

collicules supérieurs pourraient être le substrat neural sous-tendant le supra-GR chez les individus callosotomisés (Savazzi & Marzi, 2004), mais d'autres loci potentiels comme la formation réticulée ont aussi été proposés (Corballis, Hamm, Barnett, & Corballis, 2002).

Le GR se produit-il à un niveau sensoriel ou moteur?

L'échange d'informations donnant lieu au GR chez les individus callosotomisés doit indéniablement s'opérer par une voix extra-calleuse, différente de celle des normaux. Le locus du GR chez les ICD a été investigué en introduisant des manipulations sensorielles ou motrices à la tâche, de manière à affecter différemment les voies de transfert possibles. Une interprétation des résultats de telles études s'avère complexe car certaines données suggèrent que le supra-GR résulte d'une interruption du transfert d'informations de nature sensorielle alors que d'autres suggèrent plutôt qu'il résulte d'une interruption du transfert d'informations de nature motrice.

D'une part, il est soutenu que le supra-GR des individus callosotomisés s'opèrerait à un niveau sensoriel. Spécifiquement, certains ont suggéré que l'effet de sommation neurale donnant lieu au supra-GR se produirait dans les collicules supérieurs (Corballis, 1998). Cette proposition a été évaluée par un protocole reposant sur une dissociation des systèmes magnocellulaire et parvocellulaire chez des individus normaux et chez un patient callosotomisé (Savazzi & Marzi, 2004). Des stimuli

blancs, dont les longues longueurs d'onde peuvent être traitées par les collicules supérieurs, ont produit un GR excédant l'équation d'inégalité, suggérant que le supra-GR se produise en raison d'une coactivation neurale (Miller, 1982, 2004). Inversement, des stimuli violets, dont les courtes longueurs d'onde sont supposément invisibles aux neurones des collicules supérieurs, ont élicité un GR qui n'excédait pas l'équation d'inégalité, pouvant ainsi être expliqué par une approche probabiliste (Raab, 1962). Sur la base de cette dissociation, il a été suggéré qu'un relais visuel aux collicules supérieurs est nécessaire pour produire un effet de sommation neurale interhémisphérique, autant chez les normaux que chez les patients callosotomisés. À l'inverse, sans contribution colliculaire, seul un GR élicité sur la base d'une sommation probabiliste peut se produire.

Un support additionnel suggérant que les collicules supérieurs pourraient être le substrat neural de la sommation responsable du supra-GR provient des propriétés d'intégration multisensorielle de ces structures. Les collicules supérieurs sont notamment composés de neurones multisensoriels (Wallace, Meredith, & Stein, 1992). Bien qu'il ne s'agisse pas d'un argument direct, l'observation d'un GR lors de la présentation de cibles bimodales auditive et visuelle (Gielen, Schmidt, & Van den Heuvel, 1983), et visuelle et tactile (Forster, Cavina-Pratesi, Aglioti, & Berlucchi, 2002), est congruente avec l'implication de cette structure dans un mécanisme de sommation neurale. Toutefois, cette contribution a été mise en doute sur la base de l'invariabilité du GR consécutive à des manipulations de symétrie

présumées interagir avec l'organisation rétinotopique des collicules supérieurs (Roser & Corballis, 2002).

Certains modèles appuient plutôt l'hypothèse selon laquelle la coactivation hémisphérique s'opèrerait à un niveau moteur (Miller, 2004; Reuter-Lorenz et al., 1995). Pour ce faire, le modèle de Miller (2004) suppose l'implication conjointe des hémisphères dans l'initiation d'une réponse motrice, s'opposant ainsi à la position classique selon laquelle seul l'hémisphère controlatéral à la main émet la commande motrice. Ce modèle stipule que les individus callosotomisés bénéficient plus de la présentation redondante des stimuli que les individus normaux en raison de la contribution bi-hémisphérique nécessaire à l'initiation de la réponse.

Le rationel du modèle de Miller (2004) est le suivant. Chez les individus callosotomisés, puisque le corps calleux empêche l'échange rapide d'informations, une stimulation directe de chaque hémisphère permet qu'un critère de réponse donné soit rapidement atteint. À l'opposé, dans le cas d'une stimulation unilatérale, l'échange interhémisphérique prend place par une voie sous-corticale, plus lente, qui retarde la contribution motrice de l'hémisphère n'ayant pas reçu une stimulation directe. Ainsi, les individus callosotomisés bénéficient grandement de la présentation bilatérale des stimuli grâce à l'absence de nécessité de transférer un signal par des voies sous-corticales lentes. Pour leur part, les individus normaux ne bénéficient pas autant d'une stimulation bilatérale en raison d'un transfert interhémisphérique efficace via le corps calleux. Ainsi, selon ce modèle, le supra-

GR des ICD est attribuable à un ralentissement des TR aux stimuli simples plutôt qu'à un accroissement de la vitesse des TR aux stimuli redondants. Une schématisation du modèle de Miller (2004) est présentée à la Figure 3.

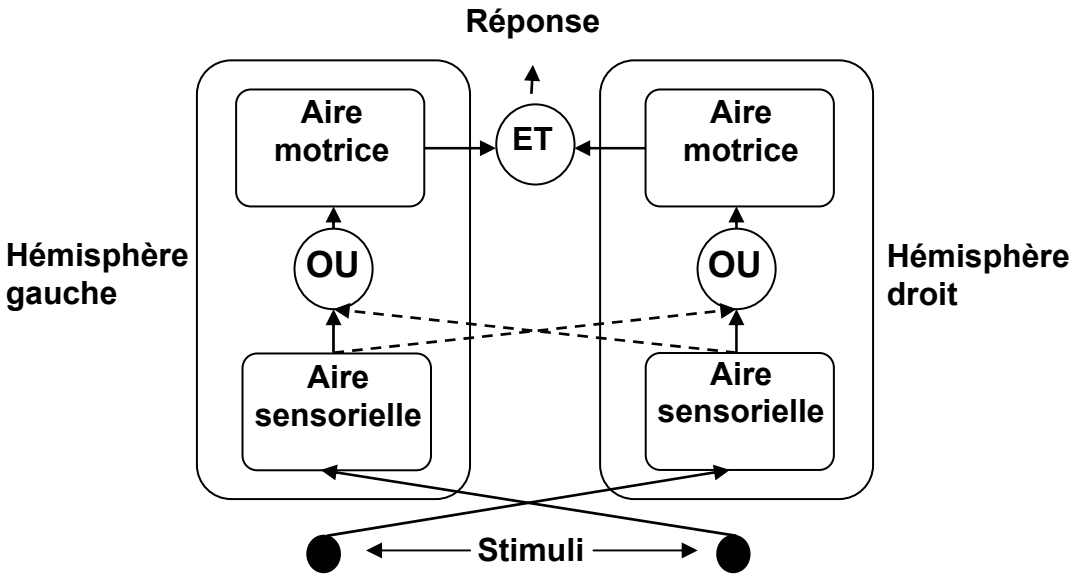

Figure 3. Le modèle de coactivation hémisphérique suppose qu'une contribution motrice de chaque hémisphère cérébral est nécessaire à l'initiation d'une réponse. Une présentation bilatérale des stimuli active les aires sensorielles de chaque hémisphère qui relaient un signal intrahémisphérique et interhémisphérique à chaque aire motrice. Chez les ICD, l'échange interhémisphérique s'opère lentement par des voies sous-corticales. Dans le cas d'une présentation bilatérale, le relais interhémisphérique n'est pas nécessaire à l'initiation de la réponse motrice en raison des échanges intrahémisphériques qui prennent place dans chaque hémisphère. Or, une présentation unilatérale exige que l'hémisphère n'ayant pas reçu de stimulation sensorielle directe attende que l'information lui parvienne par la voie sous-corticale, ce qui a pour effet d'accroître les TR. Ainsi, chez les individus callosotomisés, le supra-GR se produirait en raison d'un ralentissement des réponses aux stimuli simples.

Du support pour ce modèle provient de la constatation que les réponses aux stimuli redondants sont non seulement plus rapides, mais aussi exécutées avec plus de force que les réponses aux stimuli simples (Giray & Ulrich, 1993). Ce résultat suggère que

les stimuli redondants agissent sur des processus moteurs. Suivant cette logique, il est possible que la sommation d'activation en provenance des aires motrices contribue non seulement à diminuer les TR, mais qu'elle contribue aussi à augmenter la force avec laquelle les réponses sont produites.

Les différentes hypothèses découlant du modèle de coactivation interhémisphérique de Miller (2004) doivent toutefois être mises à l'épreuve pour en évaluer la valeur prédictive. Cette évaluation doit s'effectuer à la lumière de modèles alternatifs, dont le modèle d'interaction hémisphérique de Corballis (1998; 2002) selon lequel le GR se produirait grâce à une levée d'inhibition supposément opérée par le corps calleux. Ce modèle, à l'inverse de celui de Miller (2004), suggère que le GR est attribuable à une facilitation s'opérant lors des essais redondants plutôt qu'à un ralentissement lors des essais simples. Dans ce cas, il est supposé que la lenteur généralisée des TR des ICD, en comparaison aux individus normaux, est une conséquence générale attribuable à la chirurgie.

La différence croisé – non-croisé (DCNC)

Le paradigme de DCNC offre aussi l'opportunité d'évaluer les mécanismes en jeu dans le transfert interhémisphérique. Le paradigme classique de DCNC consiste en l'enregistrement des TR simples lors d'une tâche de détection de signal (Poffenberger, 1912). Traditionnellement, la soustraction des TR pour les réponses « non-croisées » aux TR pour les réponses « croisées » donne une différence qui

correspond au temps de transfert interhémisphérique. Cette affirmation s'appuie sur un argument anatomique. Les réponses non-croisées s'effectuent lorsque l'action motrice nécessaire à la réponse est initiée par l'hémisphère qui a reçu la stimulation sensorielle (pour une illustration de la DCNC, voir la Figure 10 de Lassonde & Ouimet, sous presse; p.56 de la présente thèse). Dans le cas d'une présentation où la relation signal-main est ipsilatérale, l'intégration sensorimotrice peut se produire au sein d'un seul et même hémisphère. À l'inverse, les réponses croisées s'effectuent lorsque l'action motrice nécessaire à la réponse est initiée par l'hémisphère qui n'a pas reçu la stimulation sensorielle. Dans le cas d'une présentation où la relation signal-main est controlatérale, l'intégration sensorimotrice est dépendante d'un transfert interhémisphérique de l'information et ne peut s'opérer au sein d'un seul et même hémisphère.

Chez les individus normaux, la DCNC est approximée à 3 ms (Bashore, 1981), ce qui représente un transfert interhémisphérique très efficace via la commissure calleuse. Chez les ICD, la DCNC atteint des valeurs alllant jusqu'à 96 ms (Aglioti, Berlucchi, Pallini, Rossi, & Tassinari, 1993; Clarke & Zaidel, 1989), ce qui représente le décours temporel d'un transfert interhémisphérique s'effectuant par l'intermédiaire de lentes voies extra-calleuses.

Selon le modèle de coactivation hémisphérique (Miller, 2004), la DCNC se produit sur la base de deux facteurs qui peuvent interagir. Le premier facteur repose sur la transmission d'informations des aires visuelles aux aires motrices qui s'opère plus

rapidement de manière intra-hémisphérique qu'inter-hémisphérique. Le second facteur repose sur la contribution de l'hémisphère controlatéral qui exerce un contrôle plus influent sur l'activation motrice totale que l'hémisphère ipsilatéral à la réponse.

La DCNC se produit-elle à un niveau sensoriel ou moteur?

L'effet de différentes manipulations sensorielles sur la DCNC a été investigué. Clarke et Zaidel (1989) ont testé l'effet de la manipulation de l'excentricité et de l'intensité lumineuse chez quatre individus présentant une section complète du corps calleux. Les résultats ont montré une importante variabilité inter-individus. La DCNC des individus normaux et d'un individu callosotomisé est demeurée inchangée par la manipulation de luminance et d'excentricité. Toutefois, la DCNC de deux individus callosotomisés a varié en fonction de l'excentricité des stimuli, mais non en fonction de la luminance. Ce dernier résultat a été interprété en tant qu'indication que le transfert interhémisphérique sous-cortical s'opèrerait par l'intermédiaire d'une voie plus sensible à l'excentricité des stimuli qu'à leur intensité lumineuse. Finalement, un quatrième patient callosotomisé a présenté un patron de résultats idiosyncratique, mettant en lumière la grande variabilité inter-individuelle. Un modèle de transfert interhémisphérique s'appuyant sur un échange parallèle d'informations à plusieurs niveaux a été postulé (Clarke & Zaidel, 1989). Ils suggèrent que les échanges interhémisphériques peuvent simultanément s'opérer

aux niveaux visuel et moteur, et que le premier traitement complété contribue au déclenchement de la réponse.

Pour leur part, Iacoboni, Fried et Zaidel (1994) ont testé l'hypothèse selon laquelle la DCNC serait sensible à des variations d'excentricité. La DCNC pré- et post-opératoire chez un individu ayant subi une section antérieure du corps calleux a été évaluée. Une DCNC dans les limites de la normale a été observée lorsque les stimuli visuels étaient présentés à quatre degrés d'excentricité alors que sa valeur était nettement supérieure lorsque les stimuli visuels étaient présentés à huit degrés d'excentricité. Ainsi, ce résultat appuie la position selon laquelle la DCNC des individus callosotomisés est sensible à des manipulations sensorielles. Néanmoins, la raison pour cette variation demeure nébuleuse. Les auteurs ont suggéré que l'augmentation de la DCNC à huit degrés d'excentricité peut être attribuée à un transfert interhémisphérique qui s'opère via des fibres calleuses de différentes tailles et vélocités au sein de la portion postérieure du corps calleux (Iacoboni et al., 1994).

Peu d'études ont toutefois évalué l'effet de manipulations motrices sur la DCNC. Un exemple de ce type de manipulations est la comparaison des TR enregistrés dans des conditions de réponses unimanuelles versus bimanuelles. Chez les individus normaux, la DCNC enregistrée bimanuellement a été estimée à 0.71 ms, soit une valeur légèrement inférieure à la DCNC enregistrée unimanuellement (Di Stefano et al., 1980). Une telle manipulation des réponses motrices a aussi été évaluée chez un individu présentant une section complète du corps calleux. Dans ce cas, bien que la

DCNC soit demeurée substantielle lorsque des réponses bimanuelles étaient enregistrées (37.9 ms), cette valeur différait significativement de la DCNC enregistrée avec des réponses unimanuelles (69.6 ms) (Aglioti et al., 1993). Il a été suggéré que la diminution des valeurs de DCNC enregistrée bimanuellement s'explique par un ralentissement de la voie ipsilatérale qui, en quelque sorte, attend la main produisant la réponse de la voie controlatérale (Berlucchi, 1995).

La coordination bimanuelle

La coordination bimanuelle offre une manière additionnelle d'investiguer le transfert interhémisphérique de l'information. Il est assumé que la synchronisation des réponses bimanuelles repose sur l'échange d'informations par la voie calleuse. Suivant cette logique, la coordination bimanuelle des individus callosotomisés devrait être affectée. Toutefois, les études menées jusqu'à présent mettent en lumière certains résultats qui paraissent contradictoires. À la suite d'une callosotomie, certaines études suggèrent l'existence d'un fort mécanisme de couplage des mains lors de mouvements bimanuels (Tuller & Kelso, 1989) alors que d'autres suggèrent plutôt une détérioration de la précision temporelle fine (Preilowski, 1972).

Certains ont rapporté que l'absence du corps calleux n'empêche pas les individus callosotomisés d'effectuer des réponses bimanuelles coordonnées lors de la détection de signaux visuels (Tuller & Kelso, 1989). Spécifiquement, il a été montré

que ces individus peinent à découpler leurs mouvements bimanuels, même lors d'une tâche où un avantage est conféré lorsque les mains agissent indépendamment.

Des déficits de coordination bimanuelle ont toutefois été documentés chez des individus ayant subi une section antérieure du corps calleux en comparant leur performance à celles de sujets contrôles épileptiques et d'individus normaux (Preilowski, 1972). La tâche consistait à tracer une ligne à l'intérieur d'un mince trottoir à l'aide de poignées, simultanément actionnées par chacune des mains, qui controllaient un crayon. La vitesse de rotation devait être ajustée séparément pour chacune des mains de manière à produire des lignes orientées selon différents angles. Les individus partiellement callosotomisés ont montré une décoordination plus importante que celle des sujets contrôles, menant l'auteur à conclure qu'une section antérieure du corps calleux interrompt le transfert interhémisphérique de l'information nécessaire à la coordination bimanuelle.

Il a aussi été suggéré que les portions antérieure et postérieure du corps calleux sont toutes deux impliquées dans la coordination bimanuelle. Deux patients ayant subi une section antérieure du corps calleux et trois patients ayant subi une section complète du corps calleux ont été comparés sur la base de leurs capacités à synchroniser la flexion de l'index ou de la main. Les différences observées entre les individus de chaque groupe laissent croire que la portion antérieure du corps calleux transfèrerait l'information temporelle de coordination relative à des indices internes

alors que la portion postérieure du corps calleux coordonnerait plutôt l'information relative aux indices externes (Eliassen, Baynes, & Gazzaniga, 2000).

OBJECTIFS ET HYPOTHÈSES DE RECHERCHE

À la lumière de cette revue de littérature, plusieurs questions émergent à l'égard du transfert interhémisphérique de l'information. La présente thèse aborde certaines d'entre elles, en se concentrant particulièrement sur la littérature portant sur les individus normaux et callosotomisés, et en visant ultimement l'amélioration de notre compréhension du rôle du corps calleux.

PREMIER ARTICLE

Le premier article consiste en une recension des écrits portant sur les signes de déconnexion calleuse que présentent les ICD pour l'ensemble des fonctions sensorielles et cognitives. Ce cadre de référence étaye une compréhension globale des spécificités neurologiques propres à cette population clinique et fournit du support empirique pour juger de l'adéquacité des différents modèles abordant le rôle du corps calleux.

DEUXIÈME ARTICLE

Le deuxième article présente une étude portant sur le GR des individus normaux et callosotomisés. Une telle étude est essentielle afin d'approfondir notre compréhension des mécanismes de transfert en jeu dans le supra-GR. Pour ce faire, la présente méthodologie permet une comparaison entre les GR des individus ayant

subi une section antérieure ou complète du corps calleux et celui des individus normaux. Spécifiquement, nous documentons les effets d'une section antérieure du corps calleux, qui interrompt le transfert d'informations motrices sans toutefois compromettre le transfert d'informations visuelles, et les effets d'une section complète du corps calleux, qui interrompt à la fois le transfert d'informations motrices et visuelles. Une comparaison des GR des différents groupes permet ainsi de fournir du support empirique à une question vivement débattue dans la littérature scientifique, en évaluant si le supra-GR est occasionné par l'interruption du transfert d'informations motrices ou sensorielles.

Différents types de traitement sont aussi comparés, indexés par des stimuli recrutant différentes voies de traitement, dans le but de comprendre les contributions corticales et sous-corticales impliquées dans le GR. Trois caractéristiques définissant les stimuli sont utilisées, chacune investiguant un niveau de traitement différent : la luminance (sous-cortical), la couleur (V4) et le mouvement (V5). En s'appuyant sur les données de Savazzi et Marzi (2004), il est attendu que le GR des individus callosotomisés produit par des stimuli définis par la luminance (pouvant être traités à un niveau sous-cortical) devrait être plus grand que celui produit par des stimuli définis par la couleur (préférentiellement traités à un niveau cortical). En corollaire, les stimuli définis par la luminance devraient aussi produire un GR plus grand que celui produit par les stimuli définis par le mouvement.

De plus, différentes conditions de présentation sont utilisées de manière à fournir du support à la position selon laquelle une présentation interhémisphérique, mais non une présentation intrahémisphérique, produit un supra-GR chez les individus callosotomisés. Une présentation de stimuli sur le méridien vertical est également utilisée afin d'investiguer si leur traitement est similaire à celui des stimuli présentés de manière inter- ou intra-hémisphérique. En raison de la stimulation redondante des hémisphères lors de la présentation de stimuli sur le méridien vertical, il est attendu que la présentation d'un stimulus dans cette condition suffise à produire un GR similaire à celui calculé sur la base de stimuli bilatéraux présentés en périphérie. Ces données permettent aussi d'évaluer le modèle de Miller (2004) selon lequel le GR est attribuable à un ralentissement de la détection des stimuli simples plutôt qu'à un accroissement de la vitesse de réponse aux stimuli bilatéraux.

TROISIÈME ARTICLE

Le troisième article présente une investigation des mécanismes de transfert sous-tendant la DCNC et l'asynchronie bimanuelle chez les individus normaux et callosotomisés. D'abord, des comparaisons entre les groupes sont effectuées sur la base de ces mesures. Puisque la DCNC et la synchronie bimanuelle reposent toutes deux sur le transfert calleux, il est attendu que les individus callosotomisés présentent des valeurs plus grandes pour les deux mesures que celles des individus normaux. Aussi, si l'information sous-tendant la DCNC, ou celle sous-tendant la synchronie bimanuelle, transfère par la portion postérieure du corps calleux, alors les individus

ayant subi une section antérieure du corps calleux devrait différer de ceux ayant subi une section complète du corps calleux. À l'inverse, si l'information sous-tendant la DCNC, ou celle sous-tendant la synchronie bimanuelle, transfère par la portion antérieure du corps calleux, alors les individus ayant subi une section antérieure du corps calleux ne devraient pas différer de ceux ayant subi une section complète.

Aussi, tout comme pour le premier article, une investigation des effets de manipulations sensorielles et attentionnelles sur la DCNC et l'asynchronie bimanuelle est conduite. Entre autres, en raison de la petite DCNC traditionnellement observée chez les individus ayant subi une section antérieure du corps calleux en comparaison à celle des individus ayant subi une section complète, nous émettons l'hypothèse que seuls ces derniers se montreront signicativement affectés par une manipulation visuelle des stimuli.

ARTICLE 1

THE SPLIT-BRAIN

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Contribution des coauteurs :
M.L.: Rédaction initiale en français, actualisation des références et révision du manuscrit final.
C.O. : Traduction vers l'anglais, actualisation des références et adaptation du manuscrit, ajout de quelques sections et plusieurs figures.

ABSTRACT

Research on split-brain individuals started to flourish approximately 70 years ago and has since then significantly contributed to our understanding of hemispheric specialization. This overview aims to capture the essential of its progress. Amongst other things, the disconnection syndrome is exposed through a description of its manifestations on sensory, motor, and cognitive functions. Ground work and recent studies on split-brain individuals are integrated.

INTRODUCTION

Our understanding of the role of the corpus callosum has significantly evolved over the last 70 years as a result of the information gathered from split-brain studies. These studies have provided a precious window into the discovery of hemispheric specialization, a phenomenon closely linked to the ontogenesis of the corpus callosum. In fact, throughout human evolution, the corpus callosum is believed to have contributed to the lateralization of functions such as language by providing a pathway through which information could rapidly circulate, decreasing the need for functional redundancy across hemispheres. Still debated is the way in which hemispheres interact through callosal pathways, namely through excitatory or inhibitory pathways. In order to investigate interhemispheric transfer, several paradigms have been developed and used with partial and total split-brain individuals as well as with callosal agenesis individuals. Studies have revealed the nature of the information that can or cannot be transferred as a consequence of a callosotomy. Recently, techniques such as diffusion tensor imaging (DTI) have arisen and furthered our understanding of interhemispheric transfer in normal individuals. Pathways through which sensory and motor information is transferred have been circumscribed, supporting the functional manifestations that have been observed for many years in callosotomized individuals. Nevertheless, several questions remain pertaining to the transfer of information between hemispheres, many involving the callosal pathways implicated in cognitive functions such as attention, language, and memory. This paper aims to provide an overview of

disconnection symptoms observed in split-brain individuals which, in turn, contribute to the furthering of our understanding of the role of the corpus callosum.

ANATOMY

The two hemispheres are linked by several fiber tracts that enable the transfer of information from one side of the brain to the other. The anterior commissure, the hippocampal commissure and the corpus callosum are amongst the pathways through which cortical information transits. The latter, the corpus callosum, is often called “the great cerebral commissure” because of its extensive distribution of axons. The total number of callosal fibers has indeed been estimated to be around 800 millions using electron microscopy (Koppel & Innocenti, 1983), with approximately 10% of cortical neurons sending their axons through the corpus callosum. This commissure is therefore the pathway with the largest number of fibers in the central nervous system, as the pyramidal pathway and the optic nerve only have approximately one million axons each.

The corpus callosum is located along the interhemispheric fissure and forms the ceiling of the lateral ventricule on a coronal plane and the ceiling of the third ventricule on a sagittal plane (Figure 1). This structure is divided into four parts extending in a rostrocaudal line: the rostrum, the genu, the body or trunk, and the splenium (Figure 1). The anterior part of the corpus callosum links the frontal lobes and transfers information pertaining to volitional attention, procedural memory and

higher mental functions (de Guise et al., 1999). The median part of the corpus callosum links the temporal and parietal lobes and transfers, amongst other things, somesthetic and auditory information. The posterior portion of the corpus callosum links the occipital lobes and contributes to the transfer of visual information (Zarei et al., 2006) (Figure 2).

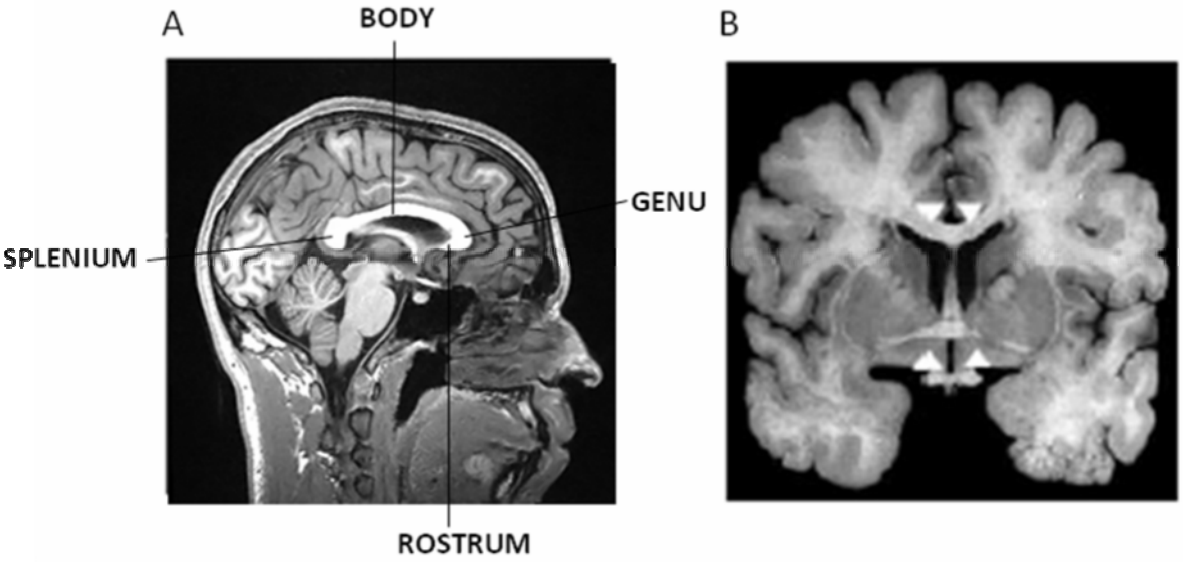

Figure 1: A. Magnetic Resonance Imaging (MRI) of a normal individual illustrating the four portions of the corpus callosum: the rostrum, the genu, the body, and the splenium on a sagittal plane. Note that on this plane, the corpus callosum constitutes the roof of the third ventricle. B. Coronal section showing how the corpus callosum constitutes the roof of the lateral ventricles.

Recent studies have further increased our understanding of the composition and distribution of callosal fibers. It has been shown that axon diameter density varies according to regions within the corpus callosum (Hofer & Frahm, 2006). Small diameter fibers are mostly concentrated in the anterior portion of the corpus callosum and also in the splenium whereas large diameter fibers are mostly

concentrated in the midbody. In addition, subdivisions of the corpus callosum have been refined as a result of research using DTI (Hofer & Frahm, 2006) and high angular resolution diffusion imaging (HARDI) tractography (Chao et al., 2009) that have contributed to the investigation of fiber projection. Of particular interest, it was found that callosal fibers transferring motor information cross the corpus callosum more posteriorly than previously assumed (Hofer & Frahm, 2006). Such studies have given rise to the refinement of callosal subdivisions as a function of projections to Brodmann's areas, enabling the visualization of neural pathways that cross the corpus callosum (Chao et al., 2009).

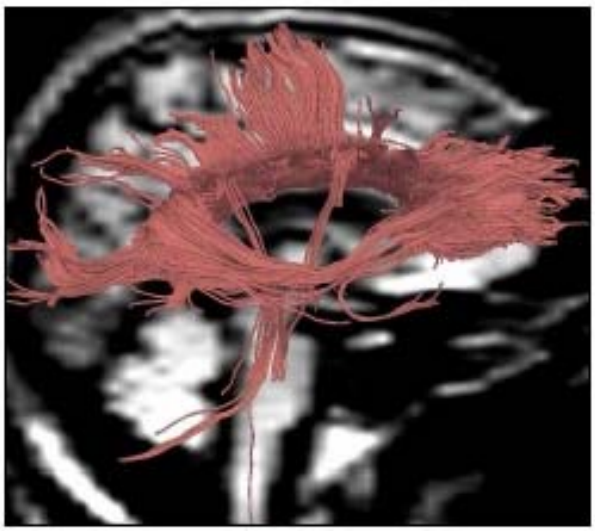

Figure 2: Representation of the fiber distribution through the corpus callosum using DTI tractography. (Figure courtesy of the Psychiatry Neuroimaging Laboratory, Brigham and Women's Hospital, Harvard Medical School, http://pnl.bwh.harvard.edu)

The corpus callosum develops *in utero* mainly between the 19th and the 21th weeks of gestation following an anterior-posterior axis. The development of the corpus callosum continues until early adulthood as callosal myelinization is influenced by

cortical maturation. Most callosal connections are homotopic, namely connecting anatomically and functionally analogous regions. Recent studies also revealed the existence of heterotopic connections, namely connections between regions dedicated to different levels of processing of a function (Clarke, 2003). As an example, primary visual areas are linked to areas involved in reading.

Structural anomalies of the corpus callosum have been identified in many neurological conditions. Studies have suggested that reduced connectivity in the corpus callosum is associated with Gilles de la Tourette syndrome, bipolar disorder, autism, dyslexia, prefrontal functions in preterm adolescents, spastic cerebral palsy and epilepsy (Tae et al., 2006). These results must be interpreted with caution as the corpus callosum is not an entity by itself, but a structure relating cortical areas. Reduced connectivity may therefore merely reflect an impairment of the cortical cells that project through the callosal structure.

HISTORICAL PERSPECTIVES

One hundred and fifty years AD, the first description of the corpus callosum was provided by Galen who widely contributed to the knowledge of general neuroanatomy by describing the corpus callosum, the ventricular system, the fornix, the tectum, the pineal and pituitary glands, and the cranial nerves (Missios, 2007). However, it was only much later that the first hypothesis on the interhemispheric linkage function of the corpus callosum was formulated by Vesalius. Following

these early investigations, two main theoretical approaches developed in parallel, one according to which callosal lesions produced a “psychic” syndrome whereas the other one claimed it produced a “disconnection” syndrome.

According to the psychic approach, the imagination and the soul lied in the corpus callosum. The psychic syndrome was described as involving strange behaviors, incoherent ideas, memory problems, and temperament modifications.

The disconnection approach emerged following the study of patients presenting particular manifestations. For example, Déjérine first described the case of a patient with a splenial lesion who showed an alexia consecutive to a right homonymous hemianopsia (Déjérine, 1892). The lesion of the splenium was interpreted as disconnecting the language areas located in the left hemisphere from the visual cortical areas of the right hemisphere and therefore disabling the decoding of verbal visual stimuli. Manifestations such as alexia and agnosia were also found in patients following partial callosotomy. For example, left hand apraxia on verbal command and left hand agraphia without any aphasic problems were interpreted as an interruption of callosal transfer between the motor areas of the right hemisphere and the area dedicated to oral and written processing located in the left hemisphere.

In the 1940s, Akelaitis investigated the first epileptic patients who underwent a surgical section of the corpus callosum to alleviate their epilepsy and showed that some of them presented with symptoms of disconnection. More specifically,

Akelaitis described the presence of “diagonistic dyspraxia”, a term coined by Akelaitis to describe the most spectacular symptom of motor disconnection in which the two hands tend to act at crosspurposes.

Breakthrough in understanding the role of the corpus callosum in humans came from experiments conducted by Sperry and collaborators on patients operated by Bogen and Vogel (Bogen & Vogel, 1962). The surgery, i.e. the callosotomy, was carried out in order to prevent the spreading of epilepsy from one hemisphere to the other. Investigation of callosotomized patients showed no intellectual impairment and grossly unaffected social behaviour. However, when submitted to tests in which information was lateralized to only one hemisphere, split-brain individuals showed evidence of hemispheric disconnection. The disconnection syndrome, which will be described in the following sections, is basically attributable to mechanisms regarding: 1) the predominantly crossed representation of sensory and motor pathways and 2) the distinct functional organization of each hemisphere.

THE DISCONNECTION SYNDROME: SENSORY AND MOTOR FUNCTIONS

MOTOR CONTROL

The motor system is organized in a crossed fashion, i.e. each hemisphere controls the contralateral part of the body at least for distal motility (Figure 3). In other

words, the left hemisphere exerts control over the right hand and the right hemisphere exerts control over the left hand. However, contrary to distal musculature such as hands and fingers that is predominantly controlled by the contralateral hemisphere, control over the proximal and axial parts of the body can be exerted by the ipsilateral hemisphere.

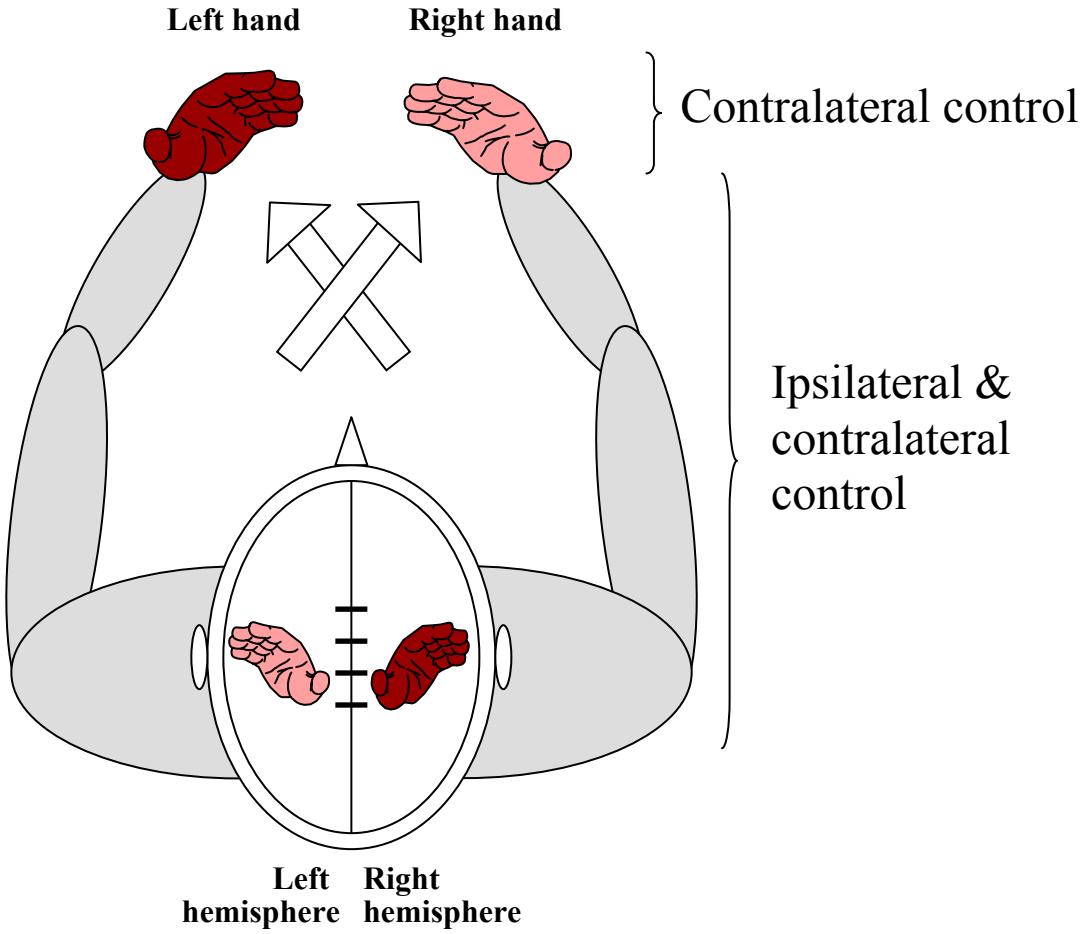

Figure 3: Representation of motor control in a neurologically-intact individual. Distal musculature such as hands and fingers are mainly controlled by the contralateral hemisphere whereas proximal and axial musculature such as arms and shoulders are both controlled by the ipsilateral and the contralateral hemispheres.

Gripping movements both necessitate proximal motion of the arm towards the target (reaching) and adjustment of the hands and fingers in order to grasp the target (grasping). Following callosotomy, each hemisphere can control the contralateral motion dedicated to grasping an object. However, the left hemisphere shows superior abilities in the choice of movements required for reaching a target. This ability holds true for any type of motor planning (Johnson, Corballis, & Gazzaniga, 1999).

More impairment derives from hemispheric disconnection in split-brain individuals, especially when unimanual responses are recorded. For example, in right-handed split-brain individuals, most symptoms exhibited by the left hand is a product of the right hemisphere being essentially aphasic (Figure 4). Writing with the right hand (commanded by the left hemisphere) is unchanged whereas writing with the left hand shows signs of agraphia. In fact, patients can exhibit left unilateral agraphia, paragraphia (misconstructing a written word) also often occurs, and the task of copying words can be executed but only using unattached letters. Similar disconnection signs also characterize left unilateral ideomotor apraxia in response to oral commands that can be observed in the postoperative phase following callosotomy. In this case, non verbal cues addressed to the right hemisphere (e.g. picture of a gesture to execute) enable the patient to easily reproduce the cued gesture.

In corollary, without the spatial support of the right hemisphere, the left hemisphere develops an apraxia-agnosia syndrome. Drawing on command or copying a complex figure, which were tasks easily executed by the right hand before the surgery, produces unrecognizable drawings once the corpus callosum has been sectioned. This condition is referred to as right unilateral constructional apraxia (Figure 4). The left hand, although exhibiting poor motor abilities for drawing, succeeds in maintaining the dynamic qualities and the three-dimensional properties exhibited before the surgery.

The disconnection of motor areas can lead to many more deficits. For example, functional efficiency of hemi-bodies relies on the bilateral integration of information between motor areas. As a consequence, without visual support, split-brain blindfolded patients are unable to reproduce right-hand limb positions with left-hand limbs and vice versa. Similarly, some studies show that bimanual coordination is affected by the section of the corpus callosum, especially when the tasks are executed without visual support (Preilowski, 1972). One of the most spectacular, although very rare exhibitions of intercortical disconnection is diagonistic dyspraxia. An often cited example of such symptom refers to a patient who was unbuttoning her blouse with her right hand while her left hand was buttoning it. Such a manifestation is only being observed in some patients for a limited time during the post-operative phase. In fact, in everyday life, split-brain individuals can do most bilateral movements. Some studies even suggested that, contrary to control individuals, they can reproduce simple drawings necessitating incompatible motion

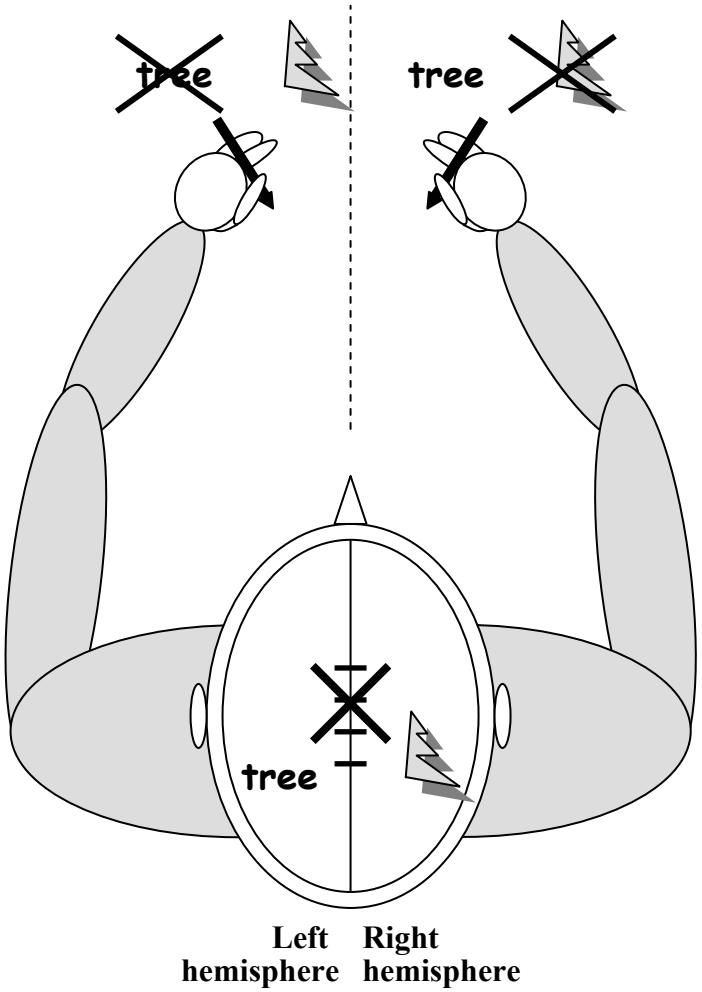

Figure 4: In split-brain individuals, information does not transit through the corpus callosum anymore. As a consequence, because of hemispheric specialization, the two hemispheres are limited in the accomplishment of specific tasks. This can give rise to manifestations such as left unilateral agraphia. For example, split-brain individuals can write the word "tree" with their right hand because writing is a function controlled by the left hemisphere. Alternatively, they can draw a picture of a tree with their left hand, but cannot write the word "tree", because drawing is a function predominantly controlled by the right hemisphere.

of the hands, as tracing a C with one hand while tracing a U with the other one, hence suggesting that spatial representations of motion of both hands is isolated in each hemisphere (Franz, Ivry, & Gazzaniga, 1996).

VISION

Due to the crossed organization of the visual system, information from each hemifield goes to the contralateral hemisphere. Only the central portion, representing the crossing zone between the two hemifields, is represented in each cerebral hemisphere. This zone occupies 2 degrees of visual angle on the vertical meridian (Fendrich, Wessinger, & Gazzaniga, 1994). In order to restrain visual input to only one hemisphere in split-brain patients, stimuli must be presented in periphery, or at least, off the bilateral representation zone. The presentation must also be very short, i.e. less than 200 ms, so that participants do not have enough time for visual saccades toward the stimulus.

When Sperry and collaborators used this technique, namely the tachitoscopic presentation, with a split-brain individual, stunning differences were observed as a function of the side of the stimulation. Stimuli presented in the right hemifield and processed by the left hemisphere could be read (Figure 4) and named (Figure 5) just like during the pre-surgery period. However, stimuli presented in the left hemifield and processed by the right hemisphere could not be named nor written down. Nevertheless, the patients were aware of the visual experience, and although they reported having seen nothing or only a flash of light, they could select with their left

hand, but not their right hand, the target object amongst several objects (LeDoux & Gazzaniga, 1978) (Figure 6). Section of the corpus callosum can therefore selectively affect verbalization of what is seen in the left hemifield and cause left homonymous hemianopsia.

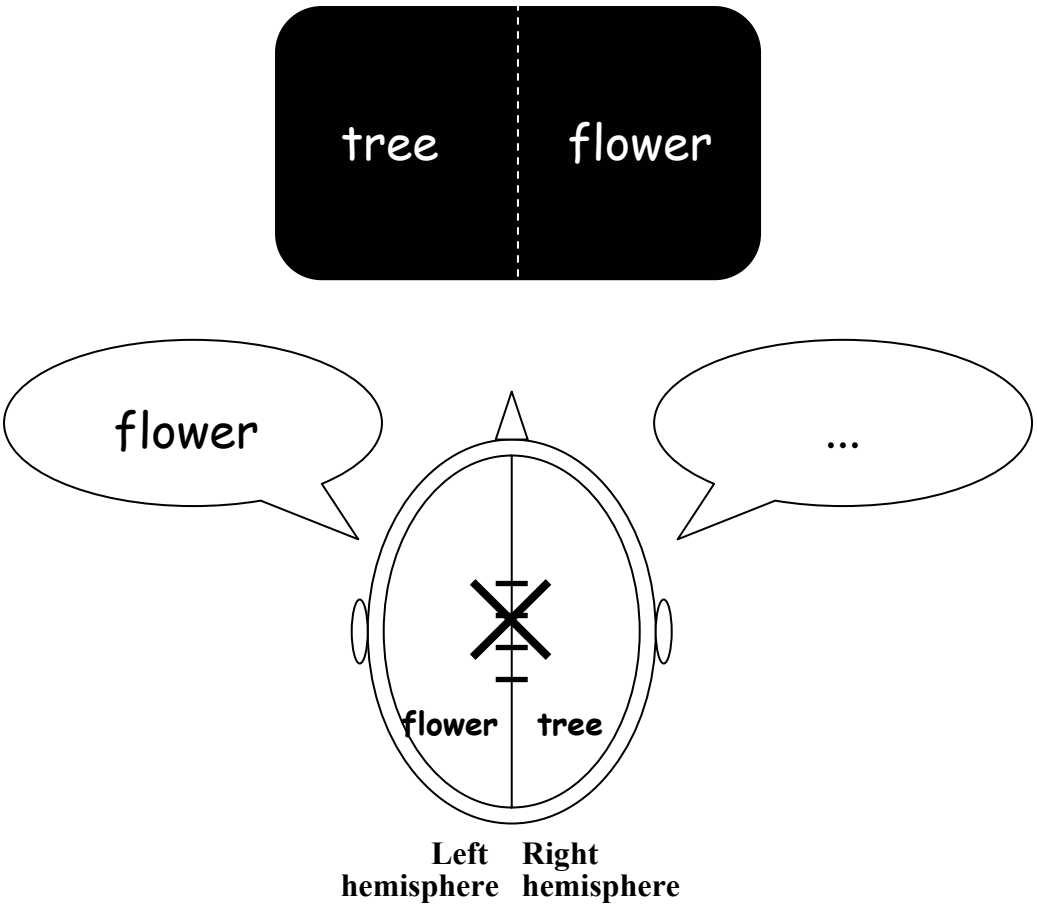

Figure 5: In split-brain individuals, when lateralizing each stimulus in one hemisphere, the left hemisphere can properly read and name "flower" whereas the right hemisphere is unable to name the word that lies in its hemifield (left hemispace).

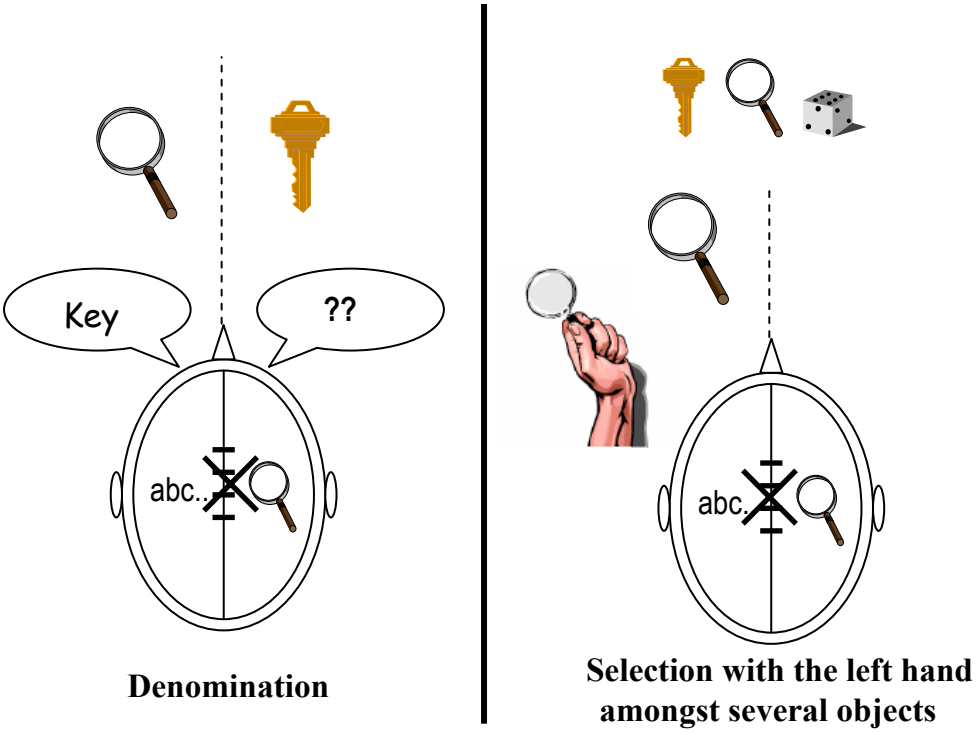

Figure 6: Although split-brain patients cannot name a lateralized stimulus presented to their right hemisphere, they can select it with their left hand (right hemisphere) amongst several objects.

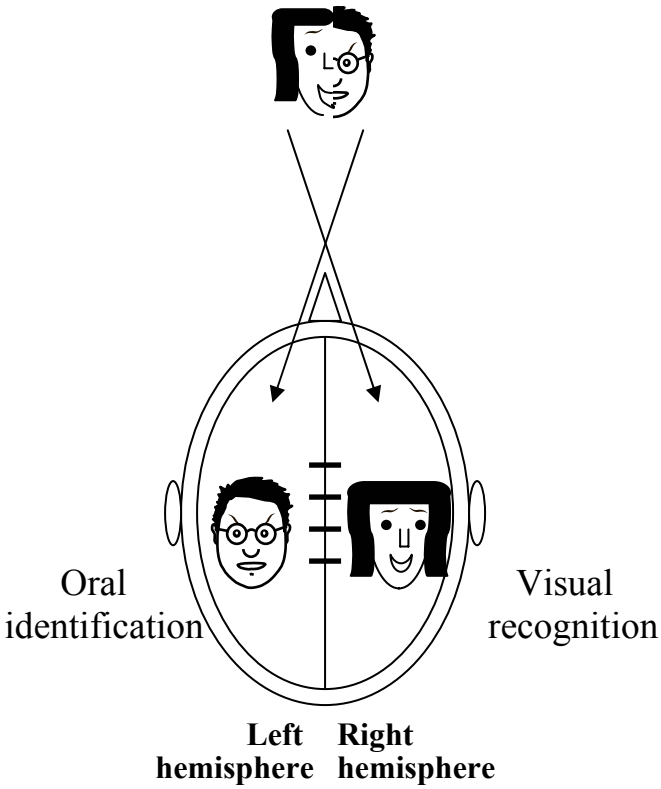

Figure 7: Illustration of chimerical figures that can be used to test hemispheric specialization in face recognition. One half of two faces are combined together to form a full face and each half is presented to different hemispheres. Consequently, identification takes place as a function of the hemisphere providing the response.

Discrimination and identification deficits can also arise for simultaneously presented bilateral stimuli. When one object is presented in each hemifield, discrimination can be impaired and each hemisphere can even independently respond to the presented objects as was shown by studies using chimerical figures (Figure 7).

SOMESTHESIS

In the brain, tactile representation of distal regions is almost exclusively contralateral (Duquette, Rainville, Alary, Lassonde, & Lepore, 2008). For this reason, hemispheric disconnection is easily identified by touch stimulation and activities requiring active tactile exploration (stereognosia, recognition of physical characteristics of stimuli).

Nociceptive and thermal information travels through the partially bilateralized pathways of the extra-lemniscal spinothalamic system and therefore does not show obvious signs of disconnection after callosotomy. Typically, without visual support, a right-handed split-brain individual is unable to name common objects palpated with the left hand (e.g. key, dice). Occasionally, when identification is achieved, it is derived from a very long and extensive exploration of the object. For example, if such a patient is manually exploring a pair of scissors, he will put his fingers into the finger-holes and touch the scissor tips before successfully identifying the object. Such manipulations can provide nociceptive cues (pointy parts of the scissors), thermal cues (whether the metal is cold), weight cues or occasionally auditory cues that can help identify the object under examination. The use of such cues, called cross-cueing, is common amongst split-brain patients who are trying to compensate for their impairments, consciously or not.

Tactile anomia of the left hand has been widely described in the literature (Gazzaniga, Bogen, & Sperry, 1962). It remains important to point out that tactile anomia of the left hand does not negate the ability to recognize an object *per se*. For example, from a lineup of several objects, a patient can easily choose which of these objects was previously held in the left hand if this same hand is used for manually identifying the objects. Tactile anomia is also different from aphasia as the right-hand/left-hemisphere complex can easily name the object. In fact, only identification necessitating verbal production is impaired when tactile stimuli are exclusively addressed to the right hemisphere.

Generally, split-brain individuals are unable to accomplish intermanual comparison tasks. One of the most sensitive tests to callosal disconnection is the crossed tactile localization. This task consists in gently pressing the finger tip of the patient while s/he is blindfolded (Figure 8). The patient is able to identify which finger was touched with the thumb of the same hand whereas the response cannot be reproduced on the fingers of the other hand.

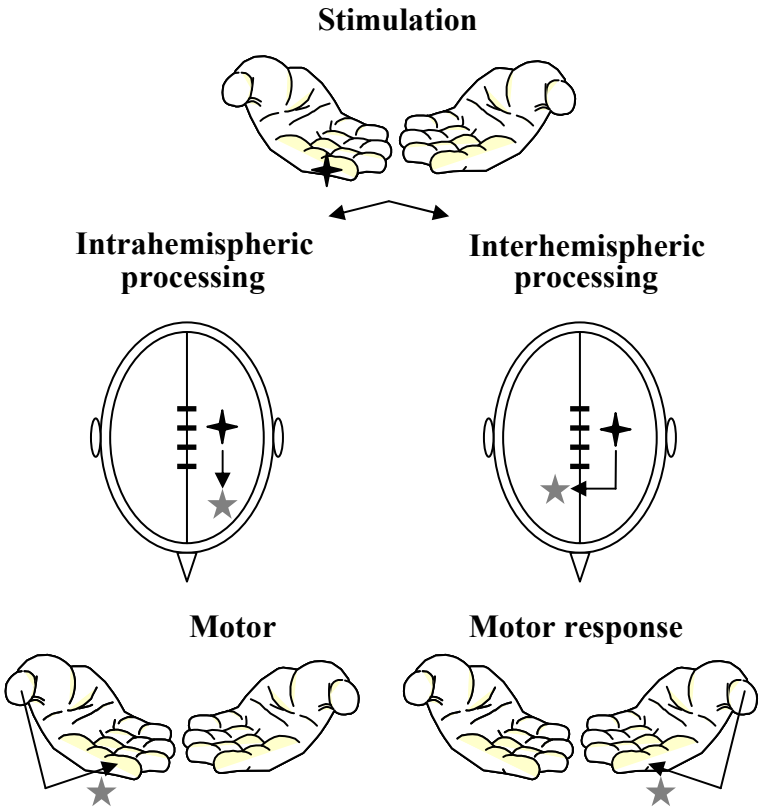

Figure 8: Test of tactile localization. Without visual support, stimulation is randomly delivered on one finger after which identification of the stimulated finger is carried out with the thumb of a given hand. In split-brain individuals, intra-manual responses usually reflect correct identification of the finger whereas inter-manual responses are often failed.

AUDITION

All auditory stimulations are processed by the two cerebral hemispheres although the contribution of the contralateral projection is considered more important than the ipsilateral one. Despite the asymmetry, because the auditory projections are bilateralized, split-brain patients can easily report verbal and non-verbal stimuli

monaurally presented because they both reach the left hemisphere, either using the ipsilateral or the contralateral connections. In dichotic listening, simultaneous presentation to each ear of two different items (eg. two different words) leads to auditory competition that can disrupt the weaker ipsilateral pathway (Kimura, 1964). Split-brain individuals then tend to report verbal stimuli heard in the right ear, stimuli processed in priority by the linguistic hemisphere (Figure 9).

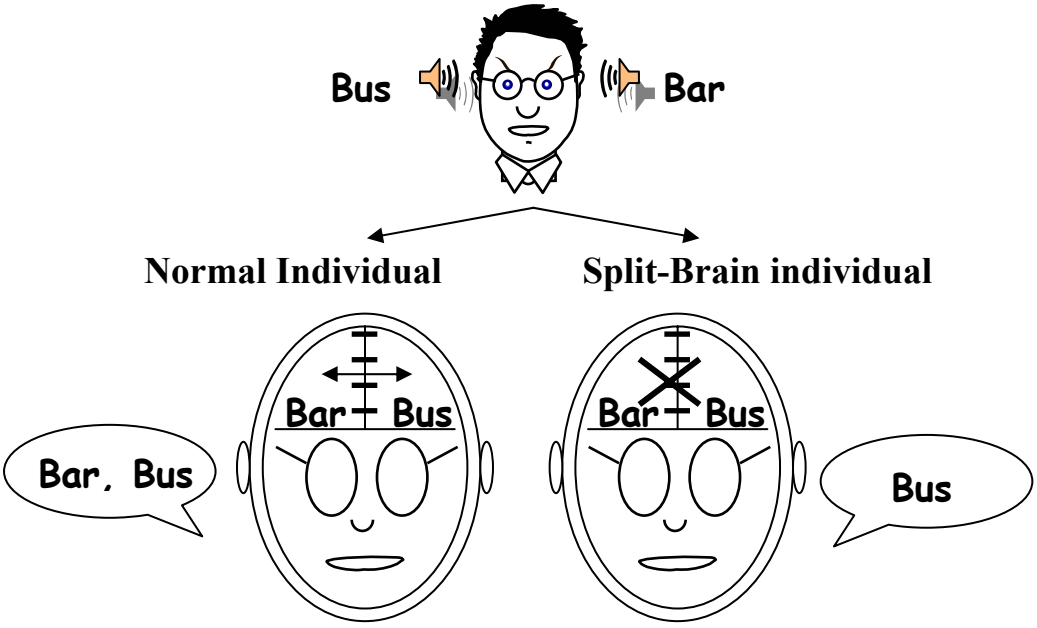

Figure 9: Dichotic listening in normal and split-brain individuals.

OLFACTION

The olfactory and taste modalities are somewhat special as they are the only senses whose pathways are not crossed. Also, it is through the anterior commissure, and not the corpus callosum, that interhemispheric communication between the cortical areas

responsible for the olfactory functions takes place. Consequently, split-brain individuals with an intact anterior commissure do not experience any differently the processing of smells (Risse, LeDoux, Springer, Wilson, & Gazzaniga, 1978). They recognize and identify smells regardless of whether they are presented to the left or right nostril. However, for patients who underwent both a section of the corpus callosum and a section of the anterior commissure, disconnection symptoms are found. Smells presented to the right nostril cannot be named but the object that evoked the smell can be found by the left hand amongst multiple objects.

VERTICAL MERIDIAN

Midline fusion is the process through which continuity is perceived through the vertical meridian. When a stimulus is presented on one side of the body or visual field and then crosses the vertical meridian to go to the other side of the body, it first excites the neurons of one hemisphere and then the neurons of the other hemisphere. However, we experience this as a unified image/sensation and no discontinuity is felt when a stimulus crosses on the other side of the brain because the second hemisphere has already been prepared by the callosal pathway to receive this stimulation. Split-brain patients do, however, experience subtle tactile and visual impairments when the stimulation is confined to the midline (Saint-Amour, Lepore, Lassonde, & Guillemot, 2004).

SENSORY-MOTOR INTEGRATION

Interhemispheric transfer (CUD)

The crossed-uncrossed difference (CUD) quantifies the interaction of the stimulus side and the responding hand in simple reaction time tasks (Poffenberger, 1912). This phenomenon has been widely used with split-brain individuals in order to assess the interhemispheric transfer time because sensory-motor integration is necessary in such a task. A lateralized stimulus is presented on the left or right of fixation and the detection time is measured by recording key presses by the right or left hand (Figure 10). The time difference obtained between the crossed trials (stimulus presented in the hemifield contralateral to the responding hand) and the uncrossed trials (stimulus presented in the hemifield ipsilateral to the responding hand) provides an estimate of the interhemispheric transfer time. In normal individuals, the CUD is approximately 3 ms, whereas it is approximately 50 ms for callosal agenesis individuals (Lassonde, Sauerwein, & Lepore, 2003), and varies from 30 to 87 ms for callosotomized individuals (Di Stefano, Sauerwein, & Lassonde, 1992).

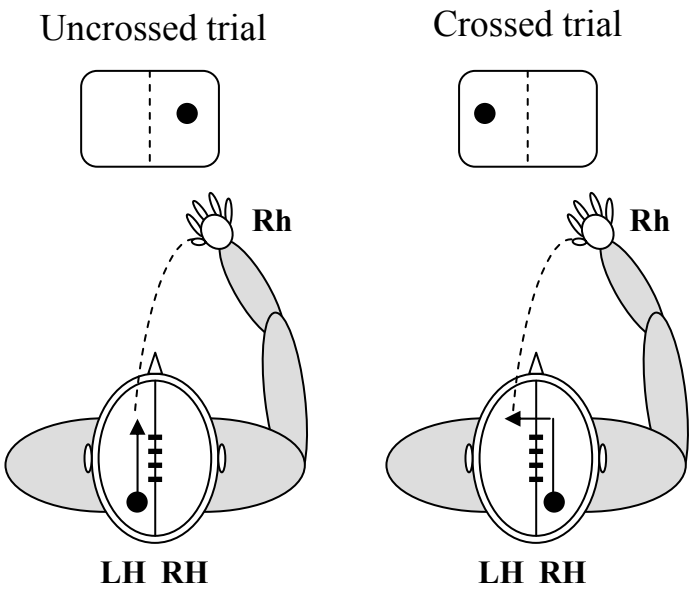

Figure 10: Illustration of the two types of trials used in a traditional crossed-uncrossed difference (CUD) paradigm. In uncrossed trials, the hemisphere receiving the visual stimulus is the same hemisphere providing the manual response. In crossed trials, the hemisphere receiving the visual stimulus transfers the signal to the other hemisphere providing the manual response. The CUD of split-brain individuals is much larger than the very small CUD of normal individuals. Note that the interhemispheric pathway illustrated here goes through the motor cortex. There may also be interhemispheric transfer through the visual cortex.

Redundant target effect (RTE)

The redundant target effect (RTE), also referred to as the redundancy gain (RG), is the reduction in reaction times observed when two, or more, stimuli are presented instead of one stimulus (Miller, 1982). Enhanced RTE (larger difference between one stimulus and multiple stimuli reaction times) has consistently been found with interhemispheric

presentation but not with intrahemispheric presentation in split-brain patients with respect to controls (Ouimet et al., 2009; Reuter-Lorenz, Nozawa, Gazzaniga, & Hughes, 1995). The first study reporting this result was that of Reuter-Lorenz and collaborators (1995) in which a total split-brain individual, J.W., showed enhanced interhemispheric RTE as compared to normal individuals, but a small intrahemispheric RTE, similar to that of normal individuals. In normal individuals, the RTE has been estimated to be 10 ms, whereas is it significantly enhanced in split-brain individuals and can reach up to 100 ms. This finding is counterintuitive because disconnected hemispheres would be expected to work more separately than hemispheres linked by the corpus callosum. Two main approaches have been postulated in order to explain this phenomenon, namely horse race models and coactivation models. Race models stipulate that reaction times to redundant stimuli are faster than reaction times to single stimuli, based on an essentially statistical explanation (Raab, 1962). Alternatively, coactivation has also been postulated, namely interhemispheric neural summation, which produces faster responses than predicted by the statistical approach. Several studies have supported the latter approach and some have even postulated that superior colliculi subserve interhemispheric summation (Corballis, 1998; Savazzi & Marzi, 2004). Also, studies have shown that partial split-brain individuals whose splenium has been preserved exhibit a smaller RTE than total split-brain individuals, suggesting that the enhanced RTE might, at least in part, arise from transfer disruption of motor information (Ouimet et al., 2009). Alternatively, other authors have suggested that the RTE can

be interpreted as an absence of the inhibitory function that the corpus callosum may exercise on the hemispheres (Zaidel & Iacoboni, 2003).

CORPUS CALLOSUM AND COGNITIVE FUNCTION

LANGUAGE

Language impairments observed following callosotomy are directly linked to the left hemisphere dominance for language. In split-brain individuals whose language is located in the left hemisphere, deficits usually include left unilateral agraphia and tactile anomia, left homonymous hemianopsia, and left ideomotor apraxia on verbal command. In the disconnected brain, the right hemisphere linguistic potential seems to be very limited. Comprehension abilities appear to selectively apply to specific word categories whereas expression abilities are considered almost non-existent (Zaidel & Iacoboni, 2003). These limits raise questions regarding whether epilepsy substantially contributes to the impairments of the right hemisphere verbal skills. In other words, epilepsy could well disrupt or progressively impair the verbal potential of the right hemisphere. Providing support to this hypothesis, it has been documented that hemispherectomized patients show a much superior linguistic performance than callosotomized patients (Smith, 1972). However, it has also been documented that several split-brain individuals show linguistic abilities in both cerebral hemispheres or, surprisingly, only in the right hemisphere (Gazzaniga,

Nass, Reeves, & Roberts, 1984). This suggests that early cerebral damage, which often characterizes split-brain individuals, can lead to cortical reorganization of linguistic functions. As an example, lexical processes have been studied in split-brain individual J. W. and it was suggested that his right hemisphere adapted to word reading by using serial processing, instead of the parallel processing usually favored (Reuter-Lorenz & Baynes, 1992). Nevertheless, verbal judgments such as word categorization (Grabowecky & Kingstone, 2004) and determining if two words are synonyms or antonyms seem to exceed the capabilities of the right hemisphere. Furthermore, only the left hemisphere displays an elaborate understanding of syntax and phonological processing (Gazzaniga, 2000).

MEMORY

Memory problems have sometimes been reported in split-brain patients, following sectioning of the anterior two-thirds or the posterior portion of the corpus callosum. Hence, sectioning the posterior portion of the corpus callosum affects free recall of verbal information without impairing recognition processes. Complementary views suggest that sectioning the anterior commissure responsible for inter-temporal communication could well impair memory functioning and that sectioning the hippocampal commissure is crucial in creating memory deficits. Nevertheless, one must keep in mind that memory deficits may well be due to pre-surgery cortical damage. More specifically, when the epileptic locus arises in the memory areas of the brain, sectioning the commissures can disturb the compensatory functions put in

place and can reintroduce the initial memory deficits (Campbell, Bogen, & Smith, 1981).

Also, the study of split-brain individuals has significantly contributed in consolidating the distinctions between the different memory systems. Amongst other things, left hemisphere superiority for semantic processing and right hemisphere superiority for episodic memory tasks have been suggested. The implication of the anterior portion of the corpus callosum has also been demonstrated in procedural memory (de Guise et al., 1999). Specifically, sectioning of the anterior corpus callosum interferes with learning of motor abilities necessitating the joint use of the two hands.

ATTENTION

Normal individuals can only focus their attention on one location at a time. In split-brain individuals, studies have shown that each cerebral hemisphere can orient its attention towards both visual hemifields. Holtzman and colleagues led a pioneering study in which, using a paradigm developed by Posner and collaborators, they found that either hemisphere can direct attention to a point in either the left or right visual field (Holtzman, Sidtis, Volpe, Wilson, & Gazzaniga, 1981). In other words, disconnected hemispheres can simultaneously and independently scan their own visual hemifield during detection and visual exploration tasks. As a result, split-brain individuals take half the time to scan images when they are dispersed amongst two visual fields as opposed to only one visual field. Also, given their ability to divide

the attentional resources between the two hemispheres, split-brain individuals can perform better than normal individuals in visual retention tasks (Gazzaniga, 2000).

OTHER CORPUS CALLOSUM ANOMALIES

PARTIAL CALLOSOTOMY

In 1961, the discovery of a patient who could write correctly with his right hand, but in an aphasic manner with his left hand, brought Geschwin and Kaplan to suspect a lesion of the corpus callosum that spared the splenium (Figure 11b) (Gazzaniga, 1970). The deficit was attributed to an interruption of communication between the motor centres of the right hemisphere (controlling left hand movements) and the language center located in the left hemisphere. Their prediction was later confirmed by autopsy. More studies carried out on patients with lesion of the splenium showed alexia without agraphia, therefore suggesting that disconnection symptoms could vary as a function of lesion localization. This prediction has since been confirmed by studies examining patients with partial section of the corpus callosum.

In the cases of patients whose epilepsy locus is located in the anterior portion of the brain, a rostral section of the corpus callosum can suffice in preventing the spread of epilepsy from one hemisphere to another. Also, the interfornix transcallosal approach used in the treatment of lesions affecting the third ventricle only

necessitates partial section of the corpus callosum. Finally, vascular or tumour lesions can specifically impair one section of the corpus callosum. Investigations of these localized lesions have contributed to the mapping of the functional organization of fibers in the corpus callosum.

CALLOSOTOMIES IN CHILDREN

Age at surgery is a determining factor in the observation of split-brain symptoms. In animals that underwent callosotomy before the end of callosal myelination, visual interhemispheric transfer was at most, only partially impaired following surgery (Ptito & Lepore, 1983). However, if surgery was carried out after the myelination period, transfer was completely impaired. Consequently, there seems to be a critical period, approximately the first 28 days in kittens, during which interhemispheric transfer can be assumed by alternative pathways. In humans, this myelination period stretches to at least until puberty (Giedd et al., 1994). If the animal model is adequate, callosotomy occurring before puberty should not abolish interhemispheric communication. Amongst children who underwent callosotomy surgery at the Saint-Justine University Hospital Center in Montreal, those who underwent the surgery before puberty showed very few disconnection deficits (Lassonde, Sauerwein, Geoffroy, & Decarie, 1986). Hence, at their first post-surgery neuropsychological assessment, the right-handed patients did not demonstrate left unilateral apraxia, were able to name objects felt with their left hand when they were blinded and succeeded in crossed localization and matching tasks.

However, reaction times were much longer and suggested compensatory limitations (Lassonde, Sauerwein, Chicoine, & Geoffroy, 1991). Conversely, for patients between the ages of 10 and 16, sectioning the corpus callosum resulted in disconnection symptoms qualitatively similar to those observed in split-brain individuals who underwent the surgery during adulthood (ideomotor apraxia, unilateral anomia, etc.). This attenuation of symptoms in pre-pubescent children probably results from cerebral plasticity occurring in the absence of the callosal system. Plasticity enables varying degrees of cerebral reorganization as a function of the damage precocity. It seems plausible that the compensatory mechanisms developed by young callosotomized individuals are similar to those expressed by callosal agenesis individuals in whom disconnection symptoms are very subtle (Grogono, 1968).

CALLOSAL AGENESIS

The congenital absence of the corpus callosum, known as callosal agenesis, is the most common natural corpus callosum pathology (Figure 11c). Callosal agenesis can be partial, total, combined to skull-facial anomalies, tumoral or constitutional (hydrocephalia and colpocephalia, microgyria, etc.). During the gestational phase, callosal agenesis can also occur due to obstruction by an interhemispheric cyst or to the presence of a lipoma exercising pressure during the development of the corpus callosum. The prevalence of callosal agenesis is approximately 1 case out of 19,000 according to post-mortem studies (Jeret, Serur, Wisniewski, & Lubin, 1987) and even more in individuals with intellectual deficiency. The overall estimate of partial

and total agenesis is approximately 0.81% (Friefeld, MacGregor, Chuang, & Saint-Cyr, 2000) but the true incidence of this malformation is possibly underestimated as it can be asymptomatic.

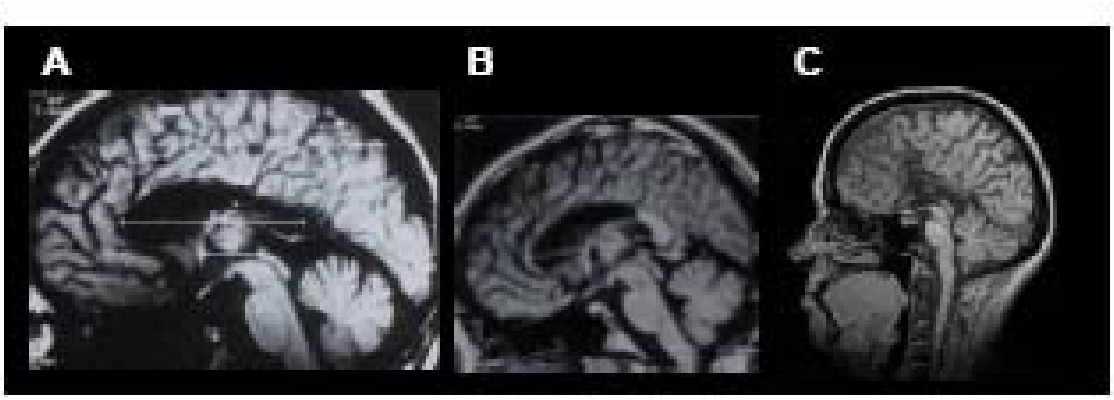

Figure 11: MRI of A) total split-brain individual, B) partial split-brain individual and C) callosal agenesis individual.

Callosal agenesis being a natural split-brain model, researchers have looked for disconnection symptoms but remained unsuccessful most of the time. Generally, agenesis individuals can name and verbally describe stimuli presented in each of their visual hemifields and do not show extinction in dichotic listening or left tactile anomia. As for interhemispheric communication, they can match manipulated objects between the two hands although difficulties arise for intermanual comparison of textures (Gazzaniga, 1970).

The apparent lack of disconnection deficits in agenesis individuals gave rise to hypotheses on the use of compensatory mechanisms. For example, bilateralization of language has been evoked to explain their ability to name objects presented in each

hemifield (Lassonde et al., 2003), although evidence supporting this hypothesis is not yet compelling. Also, the use of subtle behavioural cues (cross-cueing) has been identified as contributing to the bilateral distribution of information (Gazzaniga, 1970). For example, the non-stimulated hemisphere can use proprioceptive cues (e.g. motion) derived from responses given by the other hemisphere. However, most experimental set-up usually counters the use of cross-cueing therefore not providing a likely explanation for the lack of disconnection deficits. Another hypothesis stipulates an increased use of ipsilateral pathways co-occurring with the normal use of contralateral pathways, thus enabling a bimanual representation in each hemisphere that could explain tactile and motor compensation. This hypothesis has lately been confirmed using fMRI (Duquette et al., 2008). Finally, an increased use of residual commissures such as the anterior commissure and/or the subcortical commissures have been identified as contributing to the transfer of interhemispheric information.

No matter which compensatory mechanism is used in these individuals, it remains that interhemispheric communication has its limitations. These can be observed in tasks assessing the transfer of complex visual and tactile information, bimanual coordination, crossed tactile localization and interhemispheric transfer of unimanually learned sequences, midline integration of tactile and visual information, and binaural sound localization. The latter deficit, namely the difficulty to localize the origin of sounds presented binaurally, is accompanied by increased performance

in monaural sound localization, thus suggesting compensatory ipsilateral contribution (Lessard, Lepore, Villemagne, & Lassonde, 2002).

Because myelination of the corpus callosum is not completed before adulthood, children can show deficits similar to those exhibited by agenesis individuals. In fact, children show deficits in bimanual coordination, in tactile localization when stimuli are presented to the distal musculature, and in transfer of visuo-motor learning (Lassonde et al., 1991). Nevertheless, improvement of these functions is observed with maturation of the corpus callosum (Lassonde et al., 1991).

CONCLUSION

DYNAMIC ROLE OF THE CORPUS CALLOSUM

The role of the corpus callosum in intrahemispheric processing remains controversial. Two mutually exclusive hypotheses are proposed, namely the excitatory and the inhibitory role of the corpus callosum. The former stipulates that it acts as a bridge enabling excitatory activation of each hemisphere. The second stipulates that it prevents information transfer from one hemisphere to another through inhibitory action.

Evidence supporting the excitatory role of the corpus callosum has been gathered from epilepsy studies showing that sectioning of the corpus callosum not only

abolishes bilateral propagation of seizures, but can as well decrease, or even stop, the occurrence of epileptic seizures in its initial locus. Also, several clinical observations suggest that the corpus callosum significantly contributes to the reorganization following cerebral damage. In this context, recovery of linguistic functions has been shown to be limited in individuals whose left hemisphere was damaged simultaneously with their corpus callosum (Goldstein, 1948). This finding was supported by a post mortem anatomical study of aphasic patients in which only individuals whose corpus callosum was intact showed improvement of aphasic symptoms (Russell, 1963). Also, it has been observed that deficits accompanying unilateral pathological process in epileptic patients become more severe following commissurotomy (Campbell et al., 1981). This result can be interpreted as an increased pre-surgery contribution of the intact hemisphere, through excitatory action of the corpus callosum, alleviating symptoms associated with the damaged hemisphere.

Conversely, evidence supporting the inhibitory action of the corpus callosum has recently been gathered through transcranial magnetic stimulation (TMS) studies. In normal individuals, decrease of cortical activity triggered by TMS of the motor cortex affects contralateral movements but contributes to the improvement of ipsilateral distal movements (Kobayashi, Hutchinson, Theoret, Schlaug, & Pascual-Leone, 2004). Moreover, TMS of the parietal cortex not only gives rise to contralateral hemineglect symptoms but also induces ipsilateral visual improvement (Hilgetag, Theoret, & Pascual- Leone, 2001). These results can be interpreted as a

release of callosal inhibition by the damaged hemisphere on its contralateral counterpart.

The modulating role of the corpus callosum necessitates further investigation. It is likely that its functioning relies on the conjugation of both excitatory and inhibitory action. In fact, results gathered from metabolic and encephalographic studies conducted during cognitive tasks suggest that the corpus callosum acts as a balance between the hemispheres, thus enabling optimal integration of cortical activity. Conceptualizing the corpus callosum as a modulator of cerebral activity therefore paves the road to the elaboration of an integrated model of cerebral functioning.

REFERENCES

Bogen, J. E., & Vogel, P. J. (1962). Cerebral commissurotomy in man: Preliminary case report. *Bull Los Angeles Neurol Soc, 27*, 169-172.

Campbell, A. L., Jr., Bogen, J. E., & Smith, A. (1981). Disorganization and reorganization of cognitive and sensorimotor functions in cerebral commissurotomy. Compensatory roles of the forebrain commissures and cerebral hemispheres in man. *Brain, 104*(3), 493-511.

Chao, Y. P., Cho, K. H., Yeh, C. H., Chou, K. H., Chen, J. H., & Lin, C. P. (2009). Probabilistic topography of human corpus callosum using cytoarchitectural parcellation and high angular resolution diffusion imaging tractography. *Hum Brain Mapp, 30*(10), 3172-3187.

Clarke, J. M. (2003). Individual difference in corpus callosum morphology : To Normalize or not to normalize for brain size. In E. Zaidel & M. Iacoboni (Eds.), *The parallel brain: The cognitive neuroscience of the corpus callosum* (pp. 70-73). Cambridge: MIT Press.

Corballis, M. C. (1998). Interhemispheric Neural Summation in the Absence of the Corpus Callosum. *Brain, 121*, 1795-1807.

De Guise, E., del Pesce, M., Foschi, N., Quattrini, A., Papo, I., & Lassonde, M. (1999). Callosal and cortical contribution to procedural learning. *Brain, 122 (Pt 6)*, 1049-1062.

Déjérine, J. (1892). Contribution à l'étude anatomo-pathologique des différentes variétés de cécité verbale. *Comptes rendus hebdomadaires des séances et mémoires de la société de biologie, 44*, 61-90.

Di Stefano, M., Sauerwein, H. C., & Lassonde, M. (1992). Influence of anatomical factors and spatial compatibility on the stimulus-response relationship in the absence of the corpus callosum. *Neuropsychologia, 30*(2), 177-185.

Duquette, M., Rainville, P., Alary, F., Lassonde, M., & Lepore, F. (2008). Ipsilateral cortical representation of tactile and painful information in acallosal and callosotomized subjects. *Neuropsychologia, 46*(8), 2274-2279.

Fendrich, R., Wessinger, C. M., & Gazzaniga, M. S. (1994). Processing profiles at the retinal vertical midline of a callosotomy patient. *Society of Neuroscience Abstracts, 20*, 1579.

Franz, E., Ivry, R., & Gazzaniga, M. S. (1996). Dissociation of spatial and temporal coupling in the bimanual movements of callosotomy patients. *Psychol Sci, 7*, 306-310.

Friefeld, S., MacGregor, D., Chuang, S., & Saint-Cyr, J. (2000). Comparative study of inter- and intrahemispheric somatosensory functions in children with partial and complete agenesis of the corpus callosum. *Dev Med Child Neurol, 42*(12), 831-838.

Gazzaniga, M. S. (1970). *The bisected brain*. New York: Appelton-Century-Crofts.

Gazzaniga, M. S. (2000). Cerebral specialization and interhemispheric communication: does the corpus callosum enable the human condition? *Brain, 123*, 1293-1326.

Gazzaniga, M. S., Bogen, J. E., & Sperry, R. W. (1962). Some functional effects of sectioning the cerebral commissures. *Proc Natl Acad Sci U S A, 48*, 1765-1769.

Gazzaniga, M. S., Nass, R., Reeves, A., & Roberts, D. (1984). Neurologic perspective on right hemisphere language following surgical section of the corpus callosum. *Semin Neurol, 4*, 126-135.

Giedd, J. N., Castellanos, F. X., Casey, B. J., Kozuch, P., King, A. C., Hamburger, S. D., et al. (1994). Quantitative morphology of the corpus callosum in attention deficit hyperactivity disorder. *Am J Psychiatry, 151*(5), 665-669.

Goldstein, K. (1948). *Language and language disturbances*. New York: Grune & Stratton.

Grabowecky, M., & Kingstone, A. (2004). Can semantic information be transferred between hemispheres in the split-brain? *Brain Cogn, 55*(2), 310-313.

Grogono, J. L. (1968). Children with agenesis of the corpus callosum. *Dev Med Child Neurol, 10*(5), 613-616.

Hilgetag, C. C., Theoret, H., & Pascual-Leone, A. (2001). Enhanced visual spatial attention ipsilateral to rTMS-induced 'virtual lesions' of human parietal cortex. *Nat Neurosci, 4*(9), 953-957.

Hofer, S., & Frahm, J. (2006). Topography of the human corpus callosum revisited--comprehensive fiber tractography using diffusion tensor magnetic resonance imaging. *Neuroimage, 32*(3), 989-994.

Holtzman, J. D., Sidtis, J. J., Volpe, B. T., Wilson, D. H., & Gazzaniga, M. S. (1981). Dissociation of spatial information for stimulus localization and the control of attention. *Brain, 104*(Pt 4), 861-872.

Jeret, J. S., Serur, D., Wisniewski, K. E., & Lubin, R. A. (1987). Clinicopathological findings associated with agenesis of the corpus callosum. *Brain Dev, 9*(3), 255-264.

Johnson, S. H., Corballis, P. M., & Gazzaniga, M. S. (1999). Roles of the cerebral hemispheres in planning prehension: accuracy of movement selection following callosotomy. *J Cog Neurosci, 11* (Suppl. 85).

Kimura, D. (1964). Left-right differences in the perception of melodies. *Q J Exp Psychol, 16*, 355-356.

Kobayashi, M., Hutchinson, S., Theoret, H., Schlaug, G., & Pascual-Leone, A. (2004). Repetitive TMS of the motor cortex improves ipsilateral sequential simple finger movements. *Neurology, 62*(1), 91-98.

Koppel, H., & Innocenti, G. M. (1983). Is there a genuine exuberancy of callosal projections in development? A quantitative electron microscopic study in the cat. *Neurosci Lett, 41*(1-2), 33-40.

Lassonde, M., Sauerwein, H., Chicoine, A. J., & Geoffroy, G. (1991). Absence of disconnexion syndrome in callosal agenesis and early callosotomy: brain reorganization or lack of structural specificity during ontogeny? *Neuropsychologia, 29*(6), 481-495.

Lassonde, M., Sauerwein, H., Geoffroy, G., & Decarie, M. (1986). Effects of early and late transection of the corpus callosum in children. A study of tactile and tactuomotor transfer and integration. *Brain, 109(*Pt 5*)*, 953-967.

Lassonde, M., Sauerwein, H., & Lepore, F. (2003). Callosal agenesis. In E. Zaidel & M. Iacoboni (Eds.), *The parallel brain: The cognitive neuroscience of the corpus callosum*. Cambridge: MIT Press.

LeDoux, J. E., & Gazzaniga, M. S. (1978). *The integrated mind*. New York: Plenum Press.

Lessard, N., Lepore, F., Villemagne, J., & Lassonde, M. (2002). Sound localization in callosal agenesis and early callosotomy subjects: brain reorganization and/or compensatory strategies. *Brain, 125*(Pt 5), 1039-1053.

Miller, J. O. (1982). Divided attention: Evidence for coactivation with redundant signals. *Cognitive Psychol, 14*, 247-279.

Missios, S. (2007). Hippocrates, Galen, and the uses of trepanation in the ancient classical world. *Neurosurg Focus, 23*(1), E11.

Ouimet, C., Jolicœur, P., Miller, J., Ptito, A., Paggi, A., Foschi, N., et al. (2009). Sensory and motor involvement in the enhanced redundant target effect: A study comparing anterior- and totally split-brain individuals. *Neuropsychologia, 47*, 684-692.

Poffenberger, A. T. (1912). Reaction time to retinal retinal stimulation with special reference to the time lost in conduction through nervous centers *Arch Psychol 23*, 1-73.

Preilowski, B. F. B. (1972). Possible contribution of the anterior forebrain commissures to bilateral motor coordination. *Neuropsychologia, 10*, 267-277.

Ptito, M., & Lepore, F. (1983). Interocular transfer in cats with early callosal transection. *Nature, 301*(5900), 513-515.

Raab, D. H. (1962). Statistical facilitation of simple reaction times. *Ann N Y Acad Sci, 24*, 574-590.

Reuter-Lorenz, P., & Baynes, K. (1992). Modes of lexical access in the callosotomized brain. *J Cogn Neurosci, 4*, 155-164.

Reuter-Lorenz, P. A., Nozawa, G., Gazzaniga, M. S., & Hughes, H. C. (1995). Fate of neglected targets: a chronometric analysis of redundant target effects in the bisected brain. *J Exp Psychol Hum Percept Perform, 21*(2), 211-230.

Risse, G. L., LeDoux, J. E., Springer, S. P., Wilson, D. H., & Gazzaniga, M. S. (1978). The anterior commissure in man: Functional variation in a multisensory system. *Neuropsychologia, 16*, 23-31.

Russell, W. R. (1963). Some anatomical aspects of aphasia. *Lancet, 1*, 1173-1177.

Saint-Amour, D., Lepore, F., Lassonde, M., & Guillemot, J. P. (2004). Effective binocular integration at the midline requires the corpus callosum. N*europsychologia, 42*(2), 164-174.

Savazzi, S., & Marzi, C. A. (2004). The superior colliculus subserves interhemispheric neural summation in both normals and patients with a total section or agenesis of the corpus callosum. *Neuropsychologia, 42*, 1608-1618.

Smith, A. (1972). Dominant and nondominant hemispherectomy. In W. L. Smith (Ed.), *Drugs, development and cerebral function*. Springfield Ill.: C. C. Thomas.

Tae, W. S., Hong, S. B., Joo, E. Y., Han, S. J., Cho, J. W., Seo, D. W., et al. (2006). Structural brain abnormalities in juvenile myoclonic epilepsy patients: volumetry and voxel-based morphometry. *Korean J Radiol, 7*(3), 162-172.

Zaidel, E., & Iacoboni, M. (2003). Sensorimotor integration in the split-brain. In E. Zaidel & M. Iacoboni (Eds.), *The Parallel Brain: The cognitive neuroscience of the corpus callosum* (pp. 319-336). Cambridge: MIT Press.

Zarei, M., Johansen-Berg, H., Smith, S., Ciccarelli, O., Thompson, A. J., & Matthews, P. M. (2006). Functional anatomy of interhemispheric cortical connections in the human brain. *J Anat, 209*(3), 311-320.

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ARTICLE 2

SENSORY AND MOTOR INVOLVEMENT IN THE ENHANCED REDUNDANT TARGET EFFECT: A STUDY COMPARING ANTERIOR- AND TOTALLY SPLIT-BRAIN INDIVIDUALS

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C.O. : Analyse des résultats et rédaction de l'article
C. O., P. J., J.M., & M.L. : Interprétation des résultats
P. J., J.M., & M.L. : Révision du manuscrit

ABSTRACT

This study investigated the redundant target effect (RTE) in partial split-brain (anterior section sparing the splenium), total split-brain, and neurologically-intact individuals. All completed an RTE protocol in which targets were presented on the midline or in an inter- or intra-hemispheric manner. Stimuli of different nature (luminance, equiluminant colour, and global motion) were used separately in three experiments in order to investigate the contribution of subcortical versus cortical pathways. Despite the preservation of the splenium (the portion of the corpus callosum assumed to transfer visual information), partial split-brain individuals showed an enhanced RTE pattern as compared to neurologically-intact individuals. Total split-brain individuals showed a tendency toward larger RTEs with the luminance stimuli than with the colour and motion stimuli, whereas this was not the case for partial split-brain individuals, suggesting a contribution of the posterior portion of the corpus callosum in the RTE. It is therefore likely that both sensory and motor processes contribute to the enhanced RTE in split-brain individuals.

Keywords : Corpus callosum, redundant target effect, redundancy gain, split-brain, callosotomy

INTRODUCTION

Sensory-motor integration is an important contributor to skilled human behaviour. One way to study sensory-motor integration is through reaction time (RT) paradigms addressing the redundant target effect (RTE). The RTE, also referred to as redundancy gain (RG), is a decrease of RTs when two, or more, targets are shown rather than a single one. In the redundant condition of many RTE studies, one signal is being presented to one hemisphere and the other signal, to the other hemisphere, thus allowing for the investigation of sensory-motor interhemispheric integration. Enhanced RTE has consistently been found with interhemispheric presentation, therefore suggesting that the activation of both hemispheres lead to the occurrence of RTE (Miller, 2004).

So far, two main approaches have been proposed to account for this phenomenon, namely the horse race model and the coactivation model. The horse race model, also referred to as the probability summation model, supposes that sensory information for each stimulus is carried through separate channels (Raab, 1962). In the case of redundant targets, only the fastest of multiple stimuli is necessary to reach a criterion level of activation to trigger a motor response, where the rate of processing within a single channel is completely independent of the other one. On average, increasing the number of channels increases the probability that the RT of the fastest channel will be faster than the mean RT. Hence, strictly based on statistical assumptions, it is predicted that RTs to redundant targets are faster than RTs to single targets.

However, there is now considerable evidence that the RTE is sometimes too large to be accounted for by a strictly statistical explanation (Miller, 1982). A neural mechanism summating activation from multiple channels has been postulated by Miller (1982). In that case, the activation of different channels combines, or coactivates, in order to trigger the motor response.

RTE IN THE ABSENCE OF THE CORPUS CALLOSUM

Under interhemispheric conditions, surprisingly, individuals whose corpus callosum has been surgically sectioned show a greater RTE than callosally-intact individuals (Reuter-Lorenz, Nozawa, Gazzaniga, & Hugues, 1995). From the neural coactivation perspective, such a finding is counter-intuitive, because one would expect that the absence of corpus callosum in split-brain individuals would prevent efficient interhemispheric transfer and consequently reduce the likelihood of coactivation of the two hemispheres. However, before concluding that interhemispheric stimulation is particularly important for the RTE, the effects of intrahemispheric redundant presentation must also be explored. In fact, the few published studies including intrahemispheric redundant conditions (Iacoboni, Ptito, Weekes, & Zaidel, 2000; Pollman & Zaidel, 1999; Reuter-Lorenz et al., 1995) seem to find that split-brain as well as normal individuals produce relatively small RTEs with intrahemispheric presentation but more empirical support is needed to confirm that enhanced RTEs are strictly found in interhemispheric conditions.

Amongst the studies exploring the effects of intrahemispheric presentation, Reuter-Lorenz et al. (1995) compared the RTs to redundant targets presented within the same hemifield or between different hemifields. They tested one total split-brain individual (J.W.) and two normal individuals. As compared to normal individuals, J.W. showed an enhanced interhemispheric RTE whereas his much smaller intrahemispheric RTE was similar to those of normal individuals. This pattern led Reuter-Lorenz et al. (1995) to conclude that stimuli must be presented to both hemispheres in order to yield an enhanced RTE.

Iacoboni et al. (2000) also tested callosotomized and callosal agenesis individuals to whom they presented intrahemispheric and interhemispheric stimuli. This study was different than most RTE studies because participants were instructed to attend always to one particular frame location on the screen. A single stimulus was always presented within this frame. Depending on the condition (inter- or intrahemispheric), the redundant stimulus was presented in the unattended frame of the same hemifield or of the different hemifield. The pattern of means they obtained suggests that interhemispheric RTEs were larger than intrahemispheric RTEs for some but not all patients. However, no statistical comparison of these two conditions was carried out, so interpretation is difficult. Also, because the within/between RTE comparison was made in the presence of an unusual attentional manipulation, it is difficult to know the relevance of this manipulation to the standard RTE.

Finally, Pollman and Zaidel (1999) obtained a partially different pattern of results to that of Reuter-Lorenz et al. (1995). In a visual search paradigm in which participants had to search for inverted Ts, intrahemispheric versus interhemispheric RTE were investigated. In periphery of fixation, four Ts were always displayed, two in each hemifield, but only one or two Ts were targets (inverted Ts). Subjects had to detect as quickly as possible the presence of the target(s). Two commissurotomized individuals (N.G and L.B.) and three neurologically normal individuals were tested. Normal individuals showed RTEs both in interhemispheric and intrahemispheric presentations. Patient L.B. showed an enhanced RTE when targets were presented to both hemispheres but did not show any RTE when targets were presented to only one hemisphere. Conversely, patient N.G. showed similar RTEs within and between hemispheres. These two patients therefore showed different patterns of RTE as a function of intra- or interhemispheric presentation. It is difficult to be sure how these results relate to those obtained in most other studies of the RTE with callosotomized patients because this task required form discrimination whereas the other tasks merely required onset detection.

CORTICAL VERSUS SUBCORTICAL PROCESSING

Another relevant question in the RTE literature is that of the impact of cortical versus subcortical processing as a factor mediating the size of the RTE. Some evidence suggests that the RTE depends on sensory summation in the superior colliculi (Corballis, 1998). In order to explore the involvement of the superior

colliculi in the RTE, Corballis (1998) tested three callosotomized individuals and one acallosal individual to whom stimuli equiluminant with the background and stimuli non-equiluminant with the background were shown. The processing of equiluminant stimuli was assumed to be restricted to the cortical system whereas non-equiluminant stimuli were assumed to be processed both by the cortical and subcortical systems. Results for the callosotomized individuals showed that the RTE elicited by equiluminant stimuli was reduced as compared to the RTE elicited by non-equiluminant stimuli but no such reduction was found for the acallosal individual. It suggested that neural summation might occur at a subcortical level, probably involving the collicular visual system.

A study by Iacoboni et al. (2000) nonetheless suggests that cortical activity might act as a modulating factor on neural summation. To reach this conclusion, Iacoboni et al. (2000) used functional MRI to test two callosal agenesis individuals; one whose RTE violated probability summation models, and one whose RTE could be accounted for by such models. It was observed that task-related activity was found in the extrastriate cortex only for the individual in whom the race model inequality was violated. It was concluded that cortical modulation impacts collicular activity during parallel visuomotor processing, and consequently influences the magnitude of the RTE. In other words, it was suggested that the activity of the superior colliculi, structures in which the RTE supposedly occurs (e.g., Corballis, 1998), is likely to be modulated by cortical input.

More recently, further support was provided for the role of superior colliculi in the enhanced RTE of callosotomized individuals. Savazzi and Marzi (2004) presented monochromatic purple stimuli (claimed to be) invisible to the superior colliculi to a group of callosotomized individuals and to a group of control individuals. As opposed to the enhanced interhemispheric RTE traditionally reported for callosotomized individuals (Reuter-Lorenz et al., 1995), they found that both groups produced a similar RTE with such stimuli. Moreover, in both groups, the stimuli invisible to the superior colliculi led to an RTE consistent with the horse race model. Once again, such findings suggest that the superior colliculi play an essential role in interhemispheric neural summation. In the same context, it has further been proposed that neural summation presumably subserved via the superior colliculi is restricted to stimuli preferentially processed through the magnocellular pathway (such as luminance or motion) whereas a probabilistic summation would occur when the color-blind, parvocellular system is involved (Turatto, Mazza, Salvazzi, & Marzi, 2004). On the other hand, some researchers have argued that the superior colliculi probably do not mediate neural summation based on the finding that the enhanced RTE is maintained even when redundant targets are presented to nonhomologous locations with the two visual fields (e.g., Corballis, Hamm, Barnett, & Corballis, 2002; Roser & Corballis, 2002).

Views according to which the RTE might not strictly be a sensory phenomenon have also been expressed. It was suggested by Reuter-Lorenz et al. (1995) and more recently by Miller (2004) that coactivation might occur at a motor level. Opposed to

the classical view according to which manual control is exclusively exerted by the contralateral hemisphere, Miller's model assumes that both hemispheres contribute to the initiation of a response. Hence, it is predicted that unilateral presentation produces rather slow RTs in split-brain individuals as the hemisphere not directly stimulated awaits information from the stimulated hemisphere but can only obtain it through slow subcortical pathways. Alternatively, when interhemispheric redundant stimuli activate both hemispheres by direct visual input, both hemispheres contribute quickly to the activation of a response, leading to an enhanced RTE. The RT pattern is different for normal individuals as the corpus callosum assures fast transfer of information between hemispheres even when only one hemisphere is stimulated directly by visual input (i.e., when a single lateralized stimulus is presented). Therefore, normal individuals do not benefit as much from a bilateral presentation as do the split-brain individuals.

In the present study, we tested individuals with complete sections of the corpus callosum and individuals with partial sections. Subjects with partial sections had intact posterior callosal pathways (i.e., the splenium was intact) and sectioned anterior fibers. It was hypothesized that if the RTE occurs at a sensory level, partial split-brain individuals should show a profile of RTE similar to the one shown by normal individuals because sensory information should transit normally through the intact posterior portion of their corpus callosum. In contrast, if the RTE occurs at a motor level, partial split-brain individuals should show a RTE profile more similar

to the one presented by total split-brain individuals because they both lack the portion of the corpus callosum conveying motor information.

Neural coactivation has already been demonstrated for some types of stimuli with split-brain individuals (Iacoboni et al., 2000; Pollman & Zaidel, 1999). Therefore, the main aim of our study was not to document this neural coactivation yet again, but rather to investigate its dependence on various experimental conditions. Specifically, a further goal of this study was to analyze behaviourally whether the RTE could be elicited in the absence of the corpus callosum when using stimuli that required differential cortical and subcortical participation. Three types of stimuli were used, each defined by different attributes, namely luminance, colour, and motion. Targets defined by a luminance difference go to both subcortical (i.e., superior colliculi) and cortical systems (e.g., V1). Targets defined by colour (at equiluminance) or global motion are preferentially processed by different cortical areas (V4 and V5, respectively) (Livingstone & Hubel, 1987).

Based on the results reported by Savazzi and Marzi (2004) in a study in which they addressed the contribution of the cortical versus subcortical pathways in the RTE, it could be hypothesized that, in callosotomized individuals, luminance stimuli would produce a larger RTE than colour stimuli (at equiluminance). Additionally, still following the cortical versus subcortical distinction, it would be predicted that luminance stimuli would also produce a larger RTE than motion stimuli. The size of the RTE of callosotomized individuals would therefore differ from the RTE

amplitude of callosally-intact individuals because the latter benefit from functioning callosal pathways regardless of the attribute defining the stimuli.

Finally, we intended to investigate whether stimuli presented on the vertical meridian in a RTE experiment were processed in an inter- or intra-hemispheric fashion. On the one hand, since anything presented on the vertical meridian might be processed in both hemispheres, one could anticipate obtaining similar RTEs for redundant targets presented interhemispherically in periphery or on the vertical meridian. On the other hand, specific impairments in individuals lacking the corpus callosum were found in tasks requiring them to process information presented on the midline (Saint-Amour, Lepore, Lassonde, & Guillemot, 2004; Rivest, Cavanagh, & Lassonde, 1994). Given these discrepant considerations, it was decided to introduce a midline condition in the present study to help further our understanding of the processing of midline stimuli by these individuals.

METHODS

PARTICIPANTS

Nine split-brain individuals were tested. Eight of the nine split-brain individuals completed the full protocol and were included in the analyses. Amongst them, four had undergone complete callosotomy, and the other four had undergone anterior

callosotomy. Testing of the ninth had to be aborted halfway through testing, and the incomplete data set was not used in our analyses.

All patients had undergone complete or partial callosotomy to reduce the spread of epileptic seizures and were treated with anticonvulsive medication. Their epileptic symptoms began in childhood or in their teens (i.e., between the ages of 3 and 15) and, at the time of testing, the time elapsed since surgery ranged from 10 to 15 years. More details on patients are available in previously published papers (see references below).

Complete callosotomy

M.L. is a 28-year-old left-handed man who underwent a two-stage callosotomy at the age of 22. His postoperative IQ was of 76 (see Keenan, Wheeler, Platek, Lardi, & Lassonde, 2003). F.B. is a 26-year-old right-handed woman who underwent a two-stage complete callosotomy at the age of 16. Her postoperative IQ was of 70 (see Fabri, Polonara, Quattrini, Salvolini, Del Pesce, & Manzoni, 1999). D.D.V. is a 39-year-old right-handed man who underwent a two-stage complete callosotomy at the age of 22. His postoperative IQ was of 81 (see Fabri et al., 1999). During testing, we observed that D.D.V displayed left visual field extinction. Therefore, the two intra-hemispheric blocks were administered in the right visual field. The interhemispheric condition was unchanged as bilateral RTE have been found to be intact in hemineglect patients (Marzi et al., 1996). I.C. is a 54-year-old ambidextrous

man who underwent a two-stage complete callosotomy at the age of 33. His postoperative IQ was of 90 (see Aglioti et al., 2001).

Partial callosotomy

P.M. is a 31-year-old man. Partial callosotomy of the anterior three-quarters of the corpus callosum was performed at the age of 21. His postoperative IQ was of less than 70. A.P. is a 39-year old right-handed man. Partial callosotomy of the anterior three-quarters of the corpus callosum was performed at the age of 26 years. His postoperative IQ was of 87 (see Fabri et al., 1999). G.S. is a 44-year-old right-handed woman who was submitted to a section of the anterior four-fifths of the corpus callosum at the age of 26. Her postoperative IQ was of 99 (see Hausmann, Corballis, Fabri, Paggi, & Lewald, 2005). M.M. is a 50-year-old right-handed woman who underwent a section of the anterior three-quarters of the corpus callosum at the age of 33. Her postoperative IQ was of 86.

Also, ten neurologically-intact students at the Université de Montréal took part in this study, each completing the full protocol. All were paid for participating. All had normal or corrected-to-normal vision. All participants gave informed consent and the testing was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

Stimuli

The stimuli were disks that occupied 2° of visual angle. Six possible locations were positioned around an imaginary circle about fixation to equate eccentricity as illustrated in Figure 1A. Peripheral disks were located at 5° to the left or right of fixation. For the luminance experiment, disks were white on a black background. For the colour experiment, green disks appeared on a grey background. In that latter case, the disks and the background had previously been equated for luminance by asking participants to minimise a flicker separately for each of the six possible positions. For the motion experiment, disks in which small dots moved with a 100% coherent motion in an upward position were shown on a background of randomly positioned motionless dots. An initial display showed all of the dots for both the background and the stimulus disks. After an average interval of 500 ms after the onset of this display, the dots within one or both disks began their coherent upward movement. Participants had to detect the form defined by motion. This type of stimuli has been shown to activate MT (Vachon, Voss, Lassonde, Leroux, Mensour, Beaudoin et al., 2009). In all cases, to prevent contour detection that might be sufficient to trigger a response, Gaussian filters smoothed the edges of the disks.

For split-brain individuals, each experiment (luminance, colour, and motion) was composed of six blocks. Two blocks had interhemispheric conditions, two had intrahemispheric conditions, and two had a midline condition. One interhemispheric block used disks presented in the upper visual field whereas the other used disks

presented in the lower visual field. One intrahemispheric block used disks presented in the right visual field and the other used disks in the left visual field. In the midline condition, stimuli were presented on the vertical meridian.

For normal individuals, each experiment was composed of ten blocks. All conditions were presented twice: two interhemispheric conditions, two intrahemispheric conditions and the midline condition. Originally, a similar design was to be used for split-brain individuals but the number of trials had to be cut down from 1200 to 720 in order to maintain their vigilance throughout the experiment.

Each block was composed of 120 trials that were divided into four equiprobable events (i.e., -,-), (+,-), (-,+), (+,+), where + means the signal appeared and - means the signal did not appear (see Fig. 1). Consequently, within any given block of trials, the two chosen locations occurred independently of each other, thereby avoiding differential probability effects and contingencies among stimuli (Mordkoff & Yantis, 1991).

Each participant did forty practice trials before starting experimental blocks. All experimental blocks were themselves preceded by six practice trials. To control for general order effects, blocks were counterbalanced. For normal individuals, blocks were run in forward and then backward order whereas for callosotomized individuals, a Latin square was used to determine the block order.

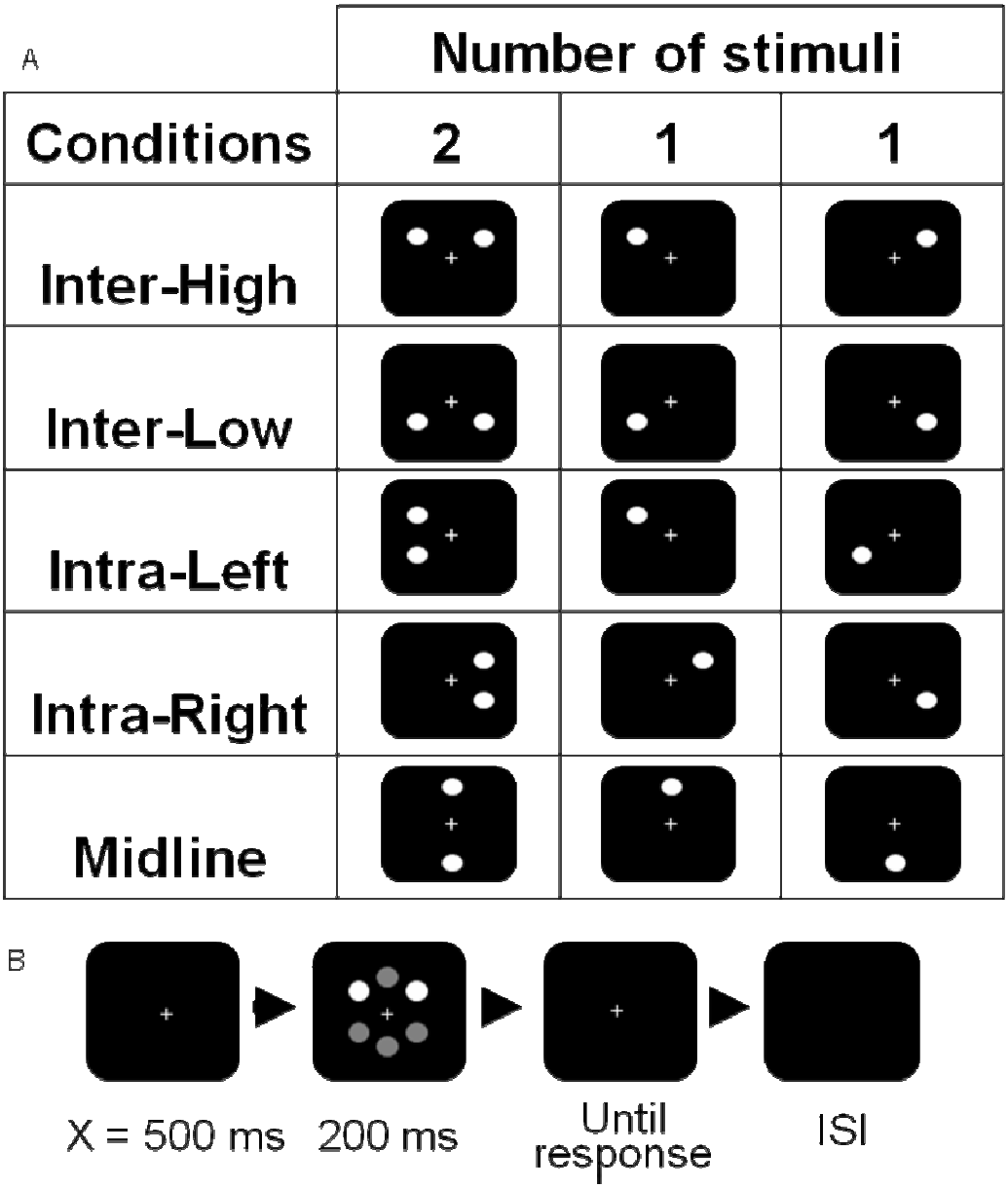

Figure 1. A: All possible conditions as a function of the number of stimuli. B: Sequence of events for the three experiments.

To ensure fixation, eye movements were tracked by two observers by the mean of a camera focused on one eye of participants. Trials with eye movements were rejected.

PROCEDURE

Each participant was seated 40 cm in front of the computer screen. Each trial began with a fixation point that participants were instructed to fixate throughout the whole duration of a trial (See Figure 1B). It stayed on the screen for an average interval of 500 ms, with this duration varying randomly between 400 ms and 600 ms from trial to trial in order to avoid anticipation responses. Then, one or two disks were presented for 200 ms while the fixation point was still displayed on the screen. Participants were allowed a duration of 1000 ms to press the response keys. As soon as a response was recorded, the fixation cross disappeared and there was a 1000 ms inter-stimulus interval (ISI). In catch trials (zero disks), to prevent participants from having to wait for two seconds before the next trial began, an average RT of the trials where stimuli appeared was calculated and the duration of the response recording interval was adjusted to match the average RT.

Participants responded bimanually by pressing the "Z" key with their left index finger and the "M" key with their right index finger as soon as they perceived any disk. This method allowed us to measure two responses per trial and to measure the RTs separately for each hand.

RESULTS

The Results section is first divided into two main subsections in which neurologically normal individuals and callosotomized individuals are examined separately. In a third subsection, all groups were put together to assess the differences between split-brain individuals (partial and total) and normal individuals, specifically with regard to RTEs.

For every trial, two RTs were recorded, one generated by the right hand and the other generated by the left hand. For normal and both partial and total split-brain individuals, Table I shows the faster of the two RTs broken down as a function of all factors, namely group, experiment, condition, and number of stimuli. Also, because different split-brain patients can behave differently (Savazzi, Fabri, Rubboli, Paggi, Tassinari, & Marzi, 2007), Table II shows the individual mean RTs of all callosotomized individuals as a function of all factors. The decision of running analyses on the fastest RTs of the two hands as opposed to on the mean RTs of the two hands was motivated by the important hand synchronization difference between normal and callosotomized individuals. In this context, the first response initiated by either of the hands was judged to provide the best information about the time course of the processes involved in the RTE. Outliers were taken out using the Van Selst and Jolicœur (1994) method, and RTs shorter than 150 ms were considered anticipatory and removed from the analyses. Once omissions and one-hand responses were taken out, the total percentage of trials excluded in each experiment

ranged from 0.3% to 3.48% in callosotomized individuals and from 0.3% to 0.4% in normal individuals.

---------- Include Tables I & II about here ----------

NEUROLOGICALLY NORMAL INDIVIDUALS

For each participant, the fastest RTs were subjected to an ANOVA. The within-subjects factors were Experiment (luminance, colour, motion), Condition (intra-, interhemispheric, midline), and Number of stimuli (1 or 2). A main effect of Number of stimuli was obtained, $F(1,9) = 92.55$, $MSE = 66.97$, $p < .0001$, indicating that normal individuals were faster responding to two stimuli (323 ms) as compared to only one stimulus (335 ms). This result confirmed the occurrence of a RTE amongst normal individuals (see Table I and Fig. 2A). Also, there was a main effect of Experiment, $F(2,18) = 21.35$, $MSE = 1492.59$, $p < .0001$, reflecting that RTs to colour stimuli (313 ms) and to luminance stimuli (318 ms) were faster than those to motion stimuli (355 ms), probably because it took more frames, and therefore more time, to see motion (see Fig. 2B). The factors Experiment and Number of stimuli did not interact, $F(2,18) = 2.65$, $MSE = 97.15$, $p > .098$, suggesting that the RTE was not influenced by the level of processing required by visual stimuli for individuals with a normal corpus callosum (see also Fig. 2C). Finally, no interaction was found between the factors Number of stimuli and Condition, $F(2,18) = 1.05$, $MSE = 37.02$, $p > .37$, indicating that the RTE in normal individuals was not modulated as a

function of interhemispheric (12 ms), intrahemispheric (10 ms), or midline (13 ms) presentation (see also Fig. 2D).

When only one stimulus is presented on the midline, its projection goes to both hemispheres. It was therefore interesting to investigate whether normal individuals would benefit from a single midline presentation as compared to a single inter- or intrahemispheric presentation. Using the same design as for the general analysis, an ANOVA was run but strictly on the single-item trials. No main effect of Condition was revealed, $F(2,18) = 0.34$, $MSE = 169.39$, $p > .71$, suggesting that single stimuli yielded similar RTs no matter whether they were presented in interhemispheric, intrahemispheric, or midline blocks. The analysis for redundant trials also revealed no main effect of Condition, $F(2,18) = 1.36$, $MSE = 183.89$, $p > .28$, confirming once again an absence of inter/intra/midline effect on the RTs of normal individuals (see Fig. 2E).

----------Insert Fig. 2A-F about here ----------

SPLIT-BRAIN INDIVIDUALS

For each participant, fastest RTs were subjected to an ANOVA. The between-subjects factor was Group (partial or total section) and the within-subjects factors were Experiment (luminance, colour, motion), Condition (intra-, interhemispheric, midline), and Number of stimuli (1 or 2). A main effect of Number of stimuli was

obtained, $F(1,6) = 29.99$, $MSE = 580.96$, $p < .002$, indicating that split-brain individuals showed a significant RTE, with average RTs of 459 and 437 ms for single and redundant stimuli, respectively (see Fig 2A). As for normal individuals, a main effect of Experiment was obtained, $F(2,12) = 7.87$, $MSE = 2870.13$, $p < .007$, showing that RTs to luminance stimuli (430 ms) and to colour stimuli (441 ms) were faster than those to motion stimuli (472 ms) (see Fig. 2B). There was no main effect of the factor Group, $F(1,6) = 0.98$, $MSE = 112268.67$, $p > .35$, neither was there an interaction between Group and Condition, $F(2,12) = 2.77$, $MSE = 966.50$, $p > .10$, or between Experiment and Number of stimuli, $F(2,12) = 1.92$, $MSE = 482.36$, $p > .18$ (see Fig. 2C). Similarly, the interaction between the factors Group, Condition, and Number of stimuli did not reach significance, $F(2,12) = 0.05$, $MSE = 519.64$, $p > .96$, suggesting that the RTE was not modulated differently for partial and total split-brain individuals by whether stimuli were presented on the midline or in intra- or inter-hemispheric fashion (see Fig. 2D). Also, an interaction between Condition and Number of stimuli was revealed, $F(2,12) = 4.80$, $MSE = 519.64$, $p < .03$, suggesting that whether one or two hemispheres were directly activated by stimuli influenced the magnitude of the RTE. Specifically, the interhemispheric condition (38 ms) led to an enhanced RTE as compared to the intrahemispheric (10 ms) or midline (18 ms) conditions (see also Fig. 2D). It is interesting to note that such a difference was not found in normal individuals. Finally, no interaction was found between Number of stimuli, Experiment, and Condition, $F(4,24) = 1.30$, $MSE = 169.24$, $p > .30$, leading to the conclusion that the enhanced RTE in the interhemispheric condition was approximately equal in all three experiments.

In order to understand more precisely the meaning of the significant interaction between the number of stimuli and the condition, we tested whether the RTE differed for each of the three possible pairs of conditions (i.e., inter-intra, inter-midline, intra-midline). When using a Bonferroni correction criterion[1] of $p < .016$ for three-pair comparisons, the analyses revealed that the interhemispheric RTE was not significantly different from the intrahemispheric RTE, $F(1,6) = 6.45$, $MSE = 1445.97$, $p < .04$, nor was it different from the midline RTE, $F(1,6) = 3.92$, $MSE = 1259.29$, $p > .095$.[1] In turn, the intrahemispheric and midline conditions were not found to be significantly different from each other, $F(1,6) = 1.68$, $MSE = 412.60$, $p > .24$. These results suggest that caution should be exercised vis-a-vis the claim that interhemispheric RTE has been consistently found to be greater than intrahemispheric RTE. On the one hand, in the present study, although the means suggest a tendency for the interhemispheric RTE to be greater than the intrahemispheric or midline RTE, such differences are not supported by statistical analyses when using a Bonferroni correction. On the other hand, given the body of literature already existing on the topic and considering that the present means go in the same direction, we suspect that accepting the null hypothesis might result in a Type II error. The results might therefore be interpreted cautiously, because it is likely that the Condition X Number of stimuli interaction is mainly driven by the contribution of a larger interhemispheric RTE as compared to the intrahemispheric RTE. In fact, the overall pattern suggests that the RTE of split-brain individuals is

[1] Post-hoc analyses were run using both Scheffe and Bonferroni corrections. Both methods led to the same conclusions.

maximized when peripheral interhemispheric stimuli are presented as compared to intrahemispheric stimuli (see Fig. 2D).

Independent analyses on respectively single and redundant trials were also run for the split-brain individuals. In the case of single-item presentations, a main effect of Condition was revealed, $F(2,12) = 7.56$, $MSE = 451.57$, $p < .008$, pointing to a significant difference between the interhemispheric (472 ms), intrahemispheric (455 ms), and midline (449 ms) conditions. The difference for all possible pairs of Conditions (inter-intra, inter-mid, intra-mid) was assessed using a Bonferroni correction criterion of $p < .016$. Although single targets presented in interhemispheric blocks led to longer RTs than single targets presented in midline blocks, $F(1,6) = 10.62$, $MSE = 600.25$, $p < .02$, this difference was not quite statistically significant. Single targets presented in intrahemispheric blocks did not lead to significantly different RTs than single targets presented in midline blocks, $F(1,6) = 0.89$, $MSE = 522.29$, $p < .38$. Also, RTs to single targets presented in interhemispheric blocks led to significantly longer RTs than single targets presented in intrahemispheric blocks, $F(1,6) = 14.64$, $MSE = 232.16$, $p < .009$ (see Fig. 2E). Examination of Table I shows that this effect was mostly apparent in response to colour and motion stimuli in total split-brain patients: the latter showed respectively a 32- and 30- ms difference between single stimuli presented interhemispherically and those presented intrahemispherically. At first sight, this last result might appear counterintuitive as there is no physical difference between one-target trials across or within hemisphere blocks, and one would expect to obtain equivalent RTs. However,

the results indicate that these conditions do differ, suggesting that the context within which single-target trials were presented had a significant impact on performance. The results can be explained in terms of different distributions of spatial attention in these two types of blocks, as will be elaborated further in the Discussion section.

Finally, an ANOVA was run exclusively on data from redundant-target trials, but this time no main effect of Condition was found, $F(2,12) = 1.24$, $MSE = 1034.57$, $p > .32$, indicating that RTs to redundant targets were not significantly different as a function of interhemispheric, intrahemispheric, and midline presentation. Obtaining RTs statistically similar in the interhemispheric and other redundant conditions might suggest, as stated by Reuter-Lorenz et al. (1995), that the RTE in split-brain individuals results from a slowing to detect single stimuli rather than from a speeding to detect redundant targets.

SPLIT-BRAIN INDIVIDUALS : INDIVIDUAL ANALYSES

Despite a similar section of the corpus callosum, split-brain individuals can behave differently from one another (Savazzi et al., 2007). It was therefore deemed relevant to report their individual results (see Table II). Additionally, analyses were run on data of each split-brain individual separately, considering trials to be the random factor, in order to assess the presence of an RTE at an individual level. These analyses asked whether the results from these trials could be generalized to the population of all possible trials for that same individual. A number of interesting

patterns of results emerged from this analysis. Firstly, based on the mean RTs in Table II, it appears that the interhemispheric RTE tends to be larger, or at least more consistent, than the intrahemispheric or midline RTE in all experiments for partial and total callosotomized individuals. For instance, in the luminance experiment, six split-brains had a significant interhemispheric RTE whereas only three split-brains had a significant RTE in the intra- or midline condition. A similar tendency was observed for the colour and motion experiments. Secondly, it is noteworthy that luminance stimuli appeared to yield more consistent RTEs than did the motion stimuli for callosotomized individuals. For all conditions combined, a total of twelve significant RTEs were found for the luminance experiment as compared to a total of only four for the motion experiment. The direction of this result is in accordance with what was expected based on a dissociation between the subcortical versus cortical pathways.

Further analyses considering trials to be the random factor were run, but this time we included data from all the callosotomized individuals rather than analyzing their data separately. We included Group, Subject, Experiment, Condition, and Number of stimuli as factors. Such analyses were useful in order to support patterns of results that emerged from the means but did not necessarily reach significance as a consequence of a lack of statistical power. Conclusions derived from these analyses can only be generalized to the specific population of split-brain individuals that we tested, but can be generalized across all trials for these individuals. For conciseness, only results that reached significance in this analysis but were previously reported as

non-significant in the general analysis are reported. In fact, all significant results of the general ANOVA remained so ($p < .01$) but additionally, a Number of stimuli X Group interaction was found, $F(1,12618) = 11.68$, $MSE = 15559.34$, $p < .001$, suggesting that our four partial split-brain individuals showed a significantly smaller RTE (16 ms) than did our four total split-brain individuals (28 ms). Also, a Number of stimuli X Experiment interaction was found, $F(2,12618) = 5.86$, $MSE = 15559.34$, $p < .003$, pointing towards a larger RTE in the luminance experiment (32 ms) as compared to the colour (16 ms) or motion (18 ms) experiments. Additionally, it is noteworthy that the Number of stimuli X Group X Experiment interaction just missed the threshold of significance, $F(2,12510) = 2.71$, $MSE = 10741.18$, $p > .067$.

Comparisons of all possible pairs of Experiments (luminance/colour, luminance/motion, and colour/motion) were carried out. Among other things, such analyses enabled us to investigate the presence of a Number of stimuli X Group X Experiment interaction for the different pairs of experiments. When a conservative Bonferroni correction was applied ($p < 0.016$), no such interaction was significant. Nevertheless, there was a tendency for these total split-brain individuals to have a larger RTE than these partial split-brain individuals with luminance stimuli (respectively 45 ms and 20 ms) as compared to colour stimuli (19 ms and 13 ms), $F(1,8466) = 4.17$, $MSE = 9257.99$, $p < .041$, or to motion stimuli (19 ms and 16 ms), $F(1,8162) = 4.12$, $MSE = 11699.36$, $p < .042$ (see Figure 2C). No trend toward such difference between the two groups of split-brain individuals was revealed when

comparing the RTE of the colour and motion experiments, F(1,8392) =0.08, MSE = 11305.54, p < .78.

NORMAL AND SPLIT-BRAIN INDIVIDUALS

One of the a priori predictions of this study stipulated that the peripheral interhemispheric condition was expected to produce different RTE patterns between total split-brain individuals and normal individuals. We also investigated whether partial split-brain individuals would show a RTE pattern similar to that of total split-brain individuals or to that of normal individuals. In order to address these questions, an ANOVA including all three groups was run on the individual participants' RTEs per se — i.e., on the difference between redundant and single trials- in the peripheral interhemispheric condition. The between-subjects factor was Group (partial split-brain individuals, total split-brain individuals, normal individuals) and the within-subjects factor was Experiment (luminance, colour, motion). A main effect of Group was obtained, $F(2,15) = 6.164$, $MSE = 790.42$, $p < .011$, confirming that, as expected, the RTE differed across groups. Partial (32 ms) and total split-brain (44 ms) individuals showed similar overall RTEs and both had an RTE that was greater than that shown by normal individuals (12 ms). Both the RTE of partial split-brain individuals, F(1,12) = 7.667, MSE = 439.84, p < .017, and the RTE of total split-brain individuals, F(1,12) = 14.413, MSE = 601.17, p < .003, were found to be greater than that of normal individuals although the partial/normal difference just failed to reach the threshold of significance once a Bonferroni correction (p < .017

rather than $p < .016$) was applied. No difference was found between the RTE of the two groups of split-brain individuals, $F(1,6) = 0.459$, $MSE = 1870.07$, $p > .523$.

A main effect of Experiment was also found, $F(2,30) = 5.988$, $MSE = 232.36$, $p < .006$, reflecting the modulation of the RTE as a function of the attribute defining the stimuli (luminance, colour, or motion). It was observed that the RTE produced by luminance stimuli (39 ms) was different from the RTEs produced by colour (29 ms) and motion (20 ms) stimuli. In order to investigate the meaning of the main effect of Experiment, separate Bonferroni-corrected tests were run to investigate whether the RTE differed across the three possible pairs of experiments (i.e., luminance/colour, luminance/motion, colour/motion). Over all groups combined, the RTE was found to be different for the experiments with luminance and motion, $F(1,15) = 11.55$, $MSE = 240.37$, $p < .004$, whereas no such difference was found for the experiments with luminance and colour, $F(1,15) = 4.81$, $MSE = 168.57$, $p < .045$, nor for the experiments with colour and motion, $F(1,15) = 2.038$, $MSE = 288.13$, $p > .17$.

Finally, an ANOVA was run in order to compare the single RTs generated by the three groups as a function of the factors Condition and Experiment. Under the assumption that a single stimulus presented on the midline would activate both hemispheres and this activation might be beneficial especially to split-brain individuals, we compared the mean RTs when a single stimulus was presented on the midline versus when a stimulus was presented off the midline (inter- or intrahemispheric). In order to obtain the most stable estimate of mean RTs of single

stimulus presented off the midline, we collapsed the single-target trials in the intra- and interhemispheric conditions. Averaging over experiments, normal individuals showed similar RTs to single stimuli on the midline versus off the midline (334ms VS 335ms), and so did partial split-brain individuals (426ms VS 430ms), whereas total split-brain individuals appeared to show a different pattern (472ms VS 498ms) (see Fig. 2F). A main effect of Group, $F(2,15)= 10.11$, $MSE = 21575.96$, $p < .002$, as well as a main effect of Condition, $F(1,15)= 8.20$, $MSE = 271.57$, $p < .012$, were found. An interaction Group X Condition was significant, $F(2,15)= 5.15$, $MSE = 271.57$, $p < .02$, suggesting that the RT pattern of single inter/intra-hemispheric stimuli versus single midline stimuli varied as a function of the groups.

In order to understand the Group X Condition interaction, pairwise comparisons of the three groups were run using a Bonferroni correction ($p < 0.016$). Partial split-brain individuals were found to produce similar RTs to those of normal individuals, $F(1,12)= 0.27$, $MSE = 46.01$, $p > .61$ and to those of total split-brains albeit at a lesser degree, $F(1,6)= 2.94$, $MSE = 167.81$, $p > .13$, whereas total split-brain individuals showed different RTs to those of normal individuals as a function of whether single stimuli were presented on or off the midline $F(1,12)= 9.38$, $MSE = 96.39$, $p < .011$. As shown in Figure 2F, the partial split-brain individuals reproduced an RT pattern that resembled more that of normal individuals whereas the total split-brain patients showed shorter RTs to stimuli presented on the midline.

DISCUSSION

According to our results, despite the preservation of the posterior portion of their corpus callosum, partial split-brain individuals, just like total split-brain individuals, differ from the RTE pattern shown by callosally-intact individuals. Specifically, both "callosal" groups showed an enhanced RTE in the interhemispheric condition whereas the normal individuals did not display any RTE differences between the inter- and intrahemispheric conditions. This pattern suggests that the absence of the anterior portion of the corpus callosum plays an important role in the occurrence of an enhanced RTE. As a consequence, it appears that the enhancement of the RTE most likely results from the interference with the transfer of motor information between hemispheres, increasing the likelihood that this enhancement occurs at a motor level (Reuter-Lorenz et al., 1995; Miller, 2004).

Our results not only suggested a motor contribution to the RTE but a tendency was also found supporting an earlier locus to the RTE. In effect, the RTE of the split-brain individuals we tested was influenced by the characteristic defining the stimuli. Specifically, the luminance RTE appeared enhanced as compared to the colour or motion RTE for total split-brain individuals but not for partial split-brain individuals (Figure 2C). Consequently, for the total split-brain individuals included in this study, the enhancement of the RTE might also have been caused, at least in part, by interference with the transfer of sensory information (Savazzi & Marzi, 2008).

Also, as previously observed by Reuter-Lorenz et al. (1995) on one split-brain individual, our data suggest that enhanced RTE occurs in the interhemispheric condition but that this effect is linked to longer RTs observed in response to single stimuli presented in the interhemispheric condition with respect to identical single stimuli presented in the intrahemispheric condition. Moreover, this effect was particularly apparent in total split-brain patients in response to colour and motion stimuli. As discussed below, these results suggest that the context within which single-target trials were presented had a significant impact on performance. The results can be explained in terms of different distributions of spatial attention in these two types of presentations.

Furthermore, our midline condition enabled us to distinguish peripheral interhemispheric presentation from midline interhemispheric presentation. Our data indicate that, in normal individuals, these two conditions are similar. However, in split-brain individuals, our data tend to suggest that only peripheral redundant interhemispheric stimulation yields enhanced RTE whereas midline redundant stimulation produces an RTE more similar to that of intrahemispheric presentation. It is interesting to note that, at least in the case of total split-brain individuals in the experiments with luminance and colour, RTs to redundant trials in the interhemispheric and midline conditions were virtually identical. Again, the enhanced RTE in the peripheral interhemispheric condition might be due to abnormally slow single peripheral interhemispheric RTs, consistent with the view that RTE is a result of a slowing of response to single targets as opposed to a

speeding of response to redundant targets (Miller, 2004; Reuter-Lorenz et al., 1995). It remains that our hypothesis according to which the RTE is due to a slowing of RTs to single stimuli contrasts with the finding reported by Savazzi et al. (2007) according to which the RTE results from a speeding up of RTs to double stimuli. Further investigation will be necessary to elucidate this issue and to understand more precisely how the two hemispheres activate the response in split-brain individuals when one or two targets are presented on the midline.

On the nature of the characteristics defining the stimuli

A tendency was revealed for the RTE of the two groups of split-brain individuals to differ on the basis of the characteristic defining the stimuli. More specifically, total split-brain individuals showed a very large luminance RTE as compared to their colour or motion RTE whereas such a difference across experiments was not apparent for partial split-brain individuals. An explanation based on a cortical versus subcortical dissociation might account for this tendency. The processing of global motion and equiluminant colour is mainly restricted to cortical pathways whereas luminance is processed both through cortical and subcortical pathways. Congruently, our results suggest that there is a characteristic specific to luminance stimuli that drives the RTE to be larger than the RTE for colour or motion in total split-brain individuals (cf Fig. 2C).

The latter result is in accordance with results reported by Savazzi and Marzi (2004) according to which the RTE of a total split-brain individual was found to be different from the RTE of normal individuals but only in a condition in which the superior colliculi could process the stimuli. Our results therefore provide further support for the role of a subcortical pathway in the RTE of totally-callosotomized individuals. This pathway or locus could well involve the superior colliculi. The fact that the superior colliculi receive an important magnocellular input from the retina has led to the suggestion that both rapid changes in luminance and motion processing should lead to increased RTE with respect to equiluminant colour in split-brain patients (Savazzi & Marzi, 2008). However, we did not find such a pattern of results: colour and motion produced RTEs of the same magnitude in total split-brains. An explanation for this might be that the motion stimuli that we used (global coherence) may be uniquely processed by cortical areas (e.g., MT or V5), thereby precluding a collicular role in the RTE effect for these stimuli. Nevertheless, the mechanisms leading to a very large luminance RTE for total split-brain individuals remain unclear and more research will be needed to clarify this question.

CONCLUSIONS DERIVED FROM SINGLE-STIMULUS PRESENTATION

The examination of the pattern of results of callosotomized individuals and normal individuals regarding single-stimulus trials provided support for Miller's model (2004) and raised unexpected attentional considerations. Firstly, Miller (2004) suggested that enhanced RTE for split-brain individuals could be explained partly in

terms of the hypothesis that both hemispheres must be activated for a response to be fast, and at least one further aspect of the results is consistent with that hypothesis. From the results in Figure 2F, it can be seen that, at least for total split-brain individuals, responses to single stimuli tended to be faster in the midline condition than in the inter- and intrahemispheric conditions, whereas this was not true for callosally-intact individuals. This is exactly the pattern that would be predicted from this hypothesis, under the assumption that midline stimuli—but not peripheral ones—activate the visual areas of both hemispheres directly.

Secondly, the analysis of the single-target RTs also suggests differences in the control of spatial attention between total split-brain individuals, partial split-brain individuals and callosally-intact individuals, of the sort suggested by Banich (2003). In the inter- and intrahemispheric conditions, single stimuli were physically the same, so it would be expected that these two conditions would yield similar RTs. In callosally-intact individuals and partial individuals, this prediction held, as the RTs to single intrahemispheric stimuli were not different from the RTs to single interhemispheric stimuli in all three experiments. Interestingly, a different pattern was shown by totally-callosotomized individuals. RTs to single interhemispheric stimuli were slower than RTs to single intrahemispheric stimuli, especially in the colour and motion experiments, despite the absence of bottom-up difference between the two conditions. This evidence suggests that attention in total split-brain individuals was deployed differently between the two hemispheres as compared to callosally-intact individuals. A straightforward conclusion regarding the partial split-

brain individuals is not possible because this group did not statistically differ from normal individuals nor from total split-brain individuals. However, mean RTs suggest they showed spatial deployment strategies more similar to those of normal individuals.

More specifically, we hypothesize that our block manipulation enabled total split-brain individuals to direct, *a priori,* their attentional resources to a single hemisphere in order to raise their efficiency at detecting stimuli in the corresponding hemifield, especially in response to stimuli that could not be processed interhemispherically via the superior colliculi (motion and colour by opposition to luminance). Whereas the single intrahemispheric presentation enabled an attentional bias, the interhemispheric presentation, where single stimuli could equally appear at the left or right of fixation, did not allow total split-brain individuals to activate *a priori* the receiving hemisphere. Consequently, total split-brain individuals produced RTs that were particularly slow in the interhemispheric presentation, whereas they benefited from an intrahemispheric presentation. In contrast, normal individuals, and perhaps partial split-brain individuals, did not compromise their attentional balance across hemispheres as the allocation of attentional resources is achieved online via the intact corpus callosum. This interpretation is in accordance with Banich's view (1998) of the corpus callosum as part of an attentional network. In effect, one of the callosal functions might be to enable a dynamic redistribution of processing across hemispheres (Banich, 2003).

One could argue that the difference found between the two single conditions (inter versus intra) could result from an advantage in motor preparation in the intrahemispheric presentation as opposed to an attentional contribution. This advantage in motor preparation for the intrahemispheric condition would result from a general level of activation in the hemisphere contralateral to the presentation. In this view, in the interhemispheric presentation, because targets are equally likely to appear in either hemifield, one hemisphere would not have the advantage of being primed. In other words, the intrahemispheric condition could prime a unilateral motor preparation through the activation of the receiving hemisphere whereas less motor priming would be possible in the interhemispheric condition.

Conclusion

In conclusion, our results suggest that total split-brain individuals and partial split-brain individuals with an anterior section of the corpus callosum both show a different pattern of RTE to that observed for normal individuals. The fact that a partial section of the corpus callosum affecting the anterior portion of the corpus callosum, presumably disturbing the transfer of motor information, results in enhanced RTE suggest the involvement of motor processes in the RTE. Moreover, given that total split-brain individuals showed an especially large RTE for luminance stimuli as compared to partial split-brain individuals, a sensory contribution to the enhanced RTE of our group of total split-brain individuals is also postulated. Although only a marginal difference between the partial split-brain individuals and

the total split-brain individuals was found, presumably because of a lack of statistical power, the pattern of means nevertheless suggests that the RTE of partial split-brain individuals could be somewhere halfway between the RTE of normal individuals and total split-brain individuals. In this view, the RTE would reflect both sensory and motor processes. More research with additional split-brain individuals will be needed to investigate further the respective contributions of such processes.

REFERENCES

Aglioti, S. M., Tassinari, G., Fabri, M., Del Pesce, M., Quattrini, A., Manzoni, T., et al. (2001). Taste laterality in the split brain. *European Journal of Neuroscience, 13*, 195-200.

Banich, M. T. (1998). The Missing Link - the Role of Interhemispheric Interaction in Attentional Processing. *Brain & Cognition, 36*, 128-157.

Banich, M. T. (2003). Interacting hemispheres : A means of modulating attention. In E. Zaidel & M. Iacoboni (Eds.), *The Parallel Brain: The cognitive neuroscience of the corpus callosum* (pp. 267-270). Cambridge: MIT Press.

Corballis, M. C. (1998). Interhemispheric Neural Summation in the Absence of the Corpus Callosum. *Brain, 121*, 1795-1807.

Corballis, M. C., Hamm, J. P., Barnett, K. J., & Corballis, P. M. (2002). Paradoxical interhemispheric summation in the split brain. *Journal of Cognitive Neuroscience, 14*, 1151-1157.

Fabri, M., Polonara, G., Quattrini, A., Salvolini, U., Del Pesce, M., & Manzoni, T. (1999). Role of the corpus callosum in the somatosensory activation of the ipsilateral cerebral cortex: an fMRI study of callosotomized patients. *European Journal of Neuroscience, 11*, 3983-3994.

Hausmann, M., Corballis, M. C., Fabri, M., Paggi, A., & Lewald, J. (2005). Sound lateralization in subjects with callosotomy, callosal agenesis, or hemispherectomy. *Cognitive Brain Research, 25*, 537-546.

Iacoboni, M., Ptito, A., Weekes, N. Y., & Zaidel, E. (2000). Parallel visuomotor processing in the split brain: cortico-subcortical interactions. *Brain, 123*, 759-769.

Keenan, J. P., Wheeler, M., Platek, S. M., Lardi, G., & Lassonde, M. (2003). Self-face processing in a callosotomy patient. *European Journal of Neuroscience, 18*, 2391-2395.

Loftus, G. R., & Masson, M. E. J. (1994). Using Confidence Intervals in within-Subject Designs. *Psychonomic Bulletin & Review, 1*(4), 476-490.

Livingstone, M. S. & Hubel, D. H. (1987). Psychophysical evidence for separate channels for the perception of form, color, movement, and depth. *Journal of Neuroscience, 7*, 3416-3468.

Marzi, C. A., Smania, N., Martini, M. C., Gambina, G., Tomelleri, G., Palamara, A., et al. (1996). Implicit Redundant Targets Effect in Visual Extinction. *Neuropsychologia, 34*, 9-22.

Miller, J. (2004). Exaggerated redundancy gain in the split brain: A hemispheric coactivation account. *Cognitive Psychology*, *49*, 118-154.

Miller, J. O. (1982). Divided attention: Evidence for coactivation with redundant signals. *Cognitive Psychology, 14*, 247-279.

Mordkoff, J. T., & Yantis, S. (1991). An interactive race model of divided attention. *Journal of Experimental Psychology : Human Perception & Performance, 17*, 520-538.

Pollmann, S., & Zaidel, E. (1999). Redundancy gains for visual search after complete commissurotomy. *Neuropsychology, 13*, 246-258.

Raab, D. H. (1962). Statistical facilitation of simple reaction times. *Transactions of the New York Academy of Sciences*, 24, 574-590.

Reuterlorenz, P. A., Nozawa, G., Gazzaniga, M. S., & Hughes, H. C. (1995). Fate of Neglected Targets - a Chronometric Analysis of Redundant Target Effects in the Bisected Brain. *Journal of Experimental: Human Perception & Performance*. 21(22):211-230.

Rivest, J., Cavanagh, P., & Lassonde, M. (1994). Interhemispheric Depth Judgement. *Neuropsychologia, 32*, 69-76.

Roser, M., & Corballis, M. C. (2002). Interhemispheric neural summation in the split brain with symmetrical and asymmetrical displays. *Neuropsychologia, 40*, 1300-1312.

Saint-Amour, D., Lepore, F., Lassonde, M., & Guillemot, J. P. (2004). Effective binocular integration at the midline requires the corpus callosum. *Neuropsychologia, 42*, 164-174.

Savazzi, S., & Marzi, C. A. (2004). The superior colliculus subserves interhemispheric neural summation in both normals and patients with a total section or agenesis of the corpus callosum. *Neuropsychologia, 42*, 1608-1618.

Savazzi, S., Fabri, M., Rubboli, G., Paggi, A., Tassinari, C. A., & Marzi, C. A. (2007). Interhemispheric transfer following callosotomy in humans: Role of the superior colliculus. *Neuropsychologia, 45*, 2417-2427.

Savazzi, S., & Marzi, C. A. (2008). Does the redundant signal effect occur at an early visual stage? *Experimental Brain Research, 184*, 275-281.

Turatto, M., Mazza, V., Savazzi, S., & Marzi, C. A. (2004). The role of the magnocellular and parvocellular systems in the redundant target effect. *Experimental Brain Research, 158*, 141-150.

Vachon, P., Voss, P., Lassonde, M., Leroux, J.-M., Mensour, B., Beaudoin G., et al. (2009). Global motion stimuli and form-from-motion stimuli: common characteristics and differential activation patterns. *International Journal of Neuroscience, 119*(10), 1584-1601.

Van Selst, M., & Jolicœur, P. (1994). A Solution to the Effect of Sample Size on Outlier Elimination. *Quarterly Journal of Experimental Psychology A, 47*, 631-650.

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Table I. Means of the fastest RTs of the bimanual responses and RTE as a function of the factors Experiment (luminance, color, and motion), Condition (inter, intra, and midline) and Group (total SB, partial SB, and callosally-intact individuals).

		Callosotomized individuals						Callosally-intact individuals		
		Total			Partial					
		Lum	Col	Mot	Lum	Col	Mot	Lum	Col	Mot
Inter	1	495	493	541	414	432	459	323	317	360
	2	431	453	513	373	400	434	311	301	352
	RTE	64	40	28	41	32	25	12	16	8
Intra	1	487	461	511	410	424	440	324	325	359
	2	458	454	504	392	429	434	311	314	354
	RTE	29	7	7	18	-5	6	13	11	5
Midline	1	468	462	487	404	425	450	330	315	357
	2	428	451	464	403	412	431	311	303	350
	RTE	40	11	23	1	13	19	19	12	7

Table II. Individual means of the fastest RTs of the bimanual responses for all callosotomized individuals as a function of the factors Experiment (luminance, color, and motion), and Condition (inter, intra, and midline), and the probability values associated with the statistical comparison of RTs to one versus two stimuli.

		Inter			Intra			Midline		
Section	Sjs	1	2	Sign.	1	2	Sign.	1	2	Sign.
LUMINANCE										
	PM	393	345	.001 *	379	370	.573	381	411	.238
	AP	353	342	.182	349	330	.065 "	354	354	.975
	GS	520	429	.000 *	507	487	.406	492	469	.327
Partial	MM	390	377	.146	404	382	.022 *	389	378	.275
	ML	505	407	.000 *	481	441	.000 *	467	429	.002 *
	FB	451	408	.020 *	441	444	.867	427	422	.834
	DDV	412	357	.000 *	360	350	.263	367	341	.004 *
Total	IC	613	552	.017 *	666	597	.010 *	612	520	.000 *
COLOUR										
	PM	374	350	.015 *	403	397	.634	399	373	.056 "
	AP	372	358	.131	366	361	.632	366	349	.185
	GS	511	453	.027 *	466	527	.008 *	466	471	.794
Partial	MM	470	441	.001 *	462	431	.002 *	468	453	.082 "
	ML	501	435	.000 *	436	421	.197	425	423	.890
	FB	471	417	.000 *	457	443	.313	436	418	.319
	DDV	376	357	.038 *	353	340	.028 *	365	356	.271
Total	IC	623	606	.422	598	612	.589	623	609	.572
MOTION										
	PM	425	390	.029 *	369	361	.386	353	344	.480
	AP	408	397	.245	406	394	.219	448	423	.116
	GS	538	499	.065 "	549	556	.780	564	542	.297
Partial	MM	463	452	.385	434	424	.435	434	413	.040 *
	ML	521	442	.000 *	500	501	.971	432	423	.439
	FB	520	535	.775	486	474	.772	439	373	.271
	DDV	443	455	.449	409	418	.401	457	495	.085 "
Total	IC	679	618	.015 *	648	625	.352	618	564	.068 "

p < .05 *, p < .10 ", Sign. : Statistical significance

FIGURE CAPTIONS

Figure 2. A: RTs to one or two stimuli as a function of groups. B: RTs to luminance, colour, and motion stimuli as a function of groups. C: RTEs for luminance, colour, and motion stimuli as a function of groups in the interhemispheric condition. D: RTEs for inter-, intrahemispheric, and midline presentation as a function of groups. E: RTs to single intra- and interhemispheric stimuli as a function of groups. F: RTs to single midline versus off-the-midline stimuli as a function of groups. Confidence intervals were calculated using the Loftus and Masson (1994) method for within-subject designs using the error term for the interaction between group and a given variable (condition, experiment, or number of stimuli) for each group separately.

Figure 2

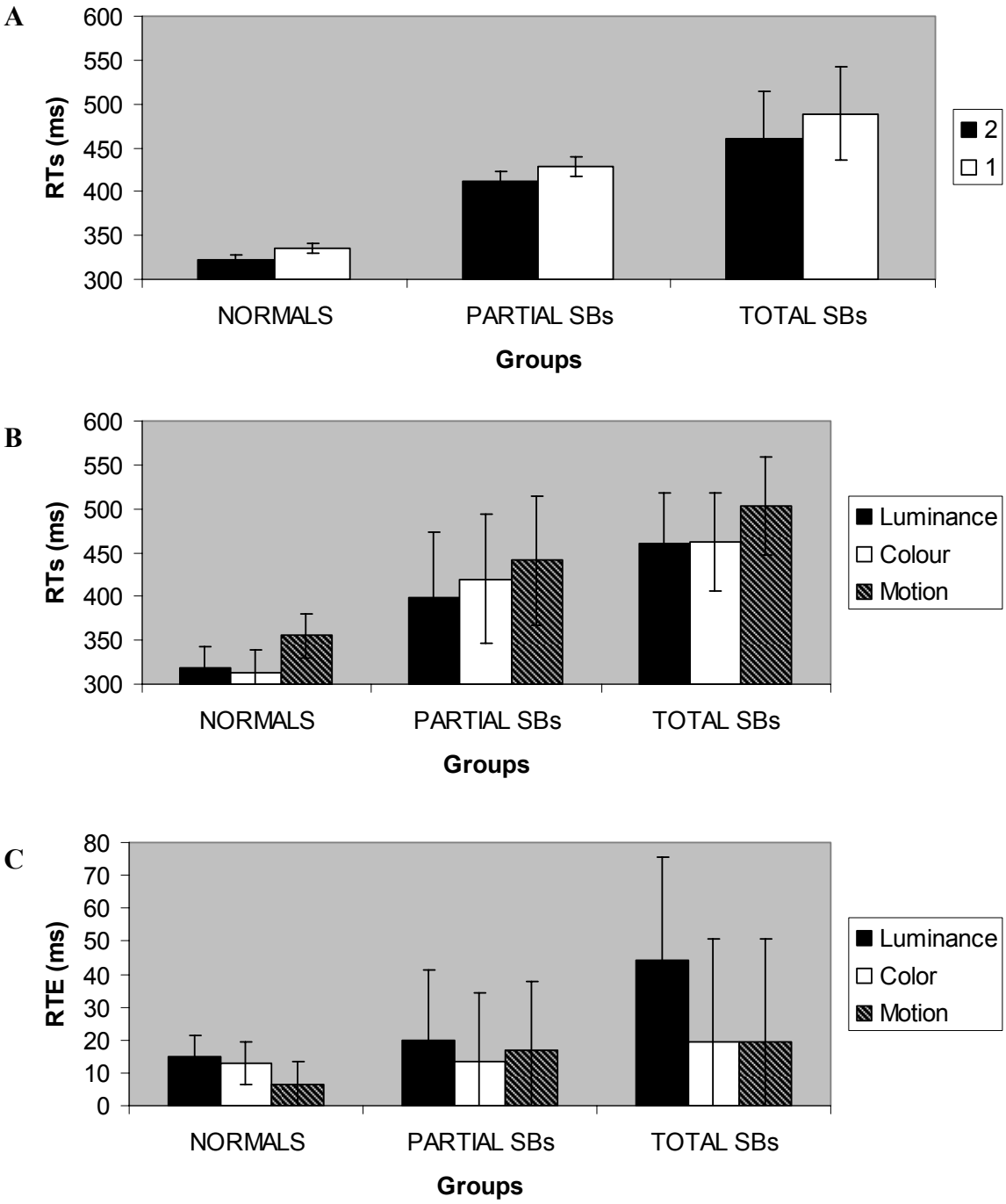
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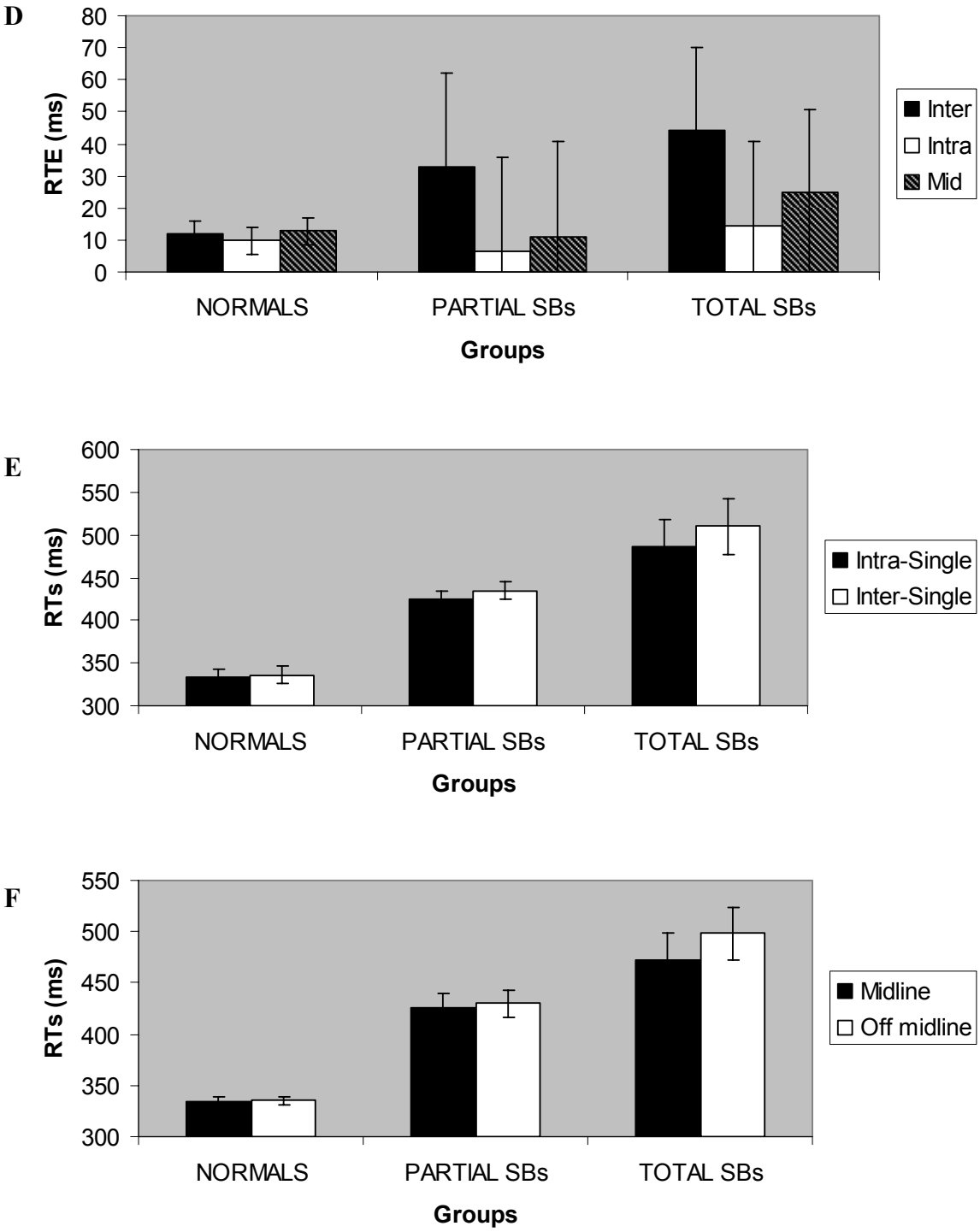
Figure 2 (suite)



NOTE- NOMENCLATURE

Une différence de nomenclature est à noter entre les deuxième et troisième articles. Les noms des facteurs *Experiment* et *Condition* du deuxième article sont plutôt désignés sous les noms de *Feature type* et *Presentation type* dans le troisième article. Dans les deux cas, ces facteurs sont équivalents et seules leurs appellations ont été modifiées.

ARTICLE 3

BIMANUAL CROSSED-UNCROSSED DIFFERENCE AND ASYNCHRONY OF NORMAL, ANTERIOR- AND TOTALLY SPLIT-BRAIN INDIVIDUALS

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J. M., P.J., M.L., & C.O. : Conception du projet
A. Pa., N.F., & A.O. : Recrutement des patients
C.O., M.L., & A.Pt. : Collecte des données
C.O. : Analyse des résultats et rédaction de l'article
C.O., J.M., & P.J. : Interprétation des résultats
P. J., J.M., & M.L. : Révision du manuscrit

ABSTRACT

This study investigated interhemispheric transfer in ten normal, four anterior-, and four totally- split-brain individuals, through measures of manual asynchrony and bimanually-recorded crossed-uncrossed difference (CUD). The CUD relied on the difference between crossed and uncrossed responses whereas the asynchrony measure relied on the reaction time difference between the two responding hands. Manipulations of sensory and attentional factors were assessed for both measures. We found a normal CUD (3.8 ms) along with an exacerbated and more variable asynchrony for partial split-brain individuals (40.8 ms) compared to normal individuals (CUD: 0.4 ms, asynchrony: 13.8 ms). In turn, the CUD of total split-brain individuals (20.4 ms) was larger than that of partial split-brain and normal individuals. Also, the asynchrony of total split-brain individuals (57.6 ms) was larger and more variable than that of normal individuals, and more variable than that of partial split-brain individuals. We interpret these results as behavioural evidence of independent mechanisms underlying the CUD and bimanual synchronization, as well as evidence of the joint involvement of both the anterior and posterior portions of the corpus callosum in bimanual coordination.

Keywords: corpus callosum, crossed-uncrossed difference (CUD), split-brain, interhemispheric transfer, bimanual coordination.

INTRODUCTION

Interhemispheric communication is essential for the integration of information across hemispheres, coherent perception, and synchronized motor control across the left and right sides of the body. The corpus callosum, with widespread fibres that link the cortex of both hemispheres from the frontal to the occipital regions, enables much of the interhemispheric communication that takes place in the human brain. The time required for information to transit from one hemisphere to the other has been a topic of keen investigation over the past century.

The pioneering study by Poffenberger (1912) used an anatomical framework to predict transfer time across hemispheres. His rationale was based on the crossed organization of the visual system and on the crossed control of distal motor movements. A lateralised visual stimulus is processed first by the hemisphere contralateral to the presentation and this hemisphere also controls the hand ipsilateral to the stimulus presentation. Hence, the hand ipsilateral to the stimulus should in theory be faster than the contralateral hand, when responding to a lateralised stimulus, given that the visual input and the motor command are integrated within a single hemisphere (uncrossed pathway). Conversely, the hand contralateral to the stimulus presentation requires the information to transfer to the other hemisphere before the motor command can be executed (crossed pathway). Poffenberger's results indeed supported these predictions because he found that reaction times (RTs) for crossed responses were longer than RTs for uncrossed

responses, suggesting that the crossed-uncrossed difference (CUD) reflects interhemispheric transfer time.

The CUD has traditionally been investigated with a paradigm consisting of the detection of lateralised stimuli using unimanual responses. In such conditions, the CUD of normal individuals has been estimated to average around 3 ms (Bashore, 1981). In similar conditions, the CUD of individuals with callosal agenesis (a congenital absence of the corpus callosum) has been reported to range between 12 and 51 ms (Clarke & Zaidel, 1989; Milner, Jeeves, Silver, Lines, & Wilson, 1985; Di Stefano, Sauerwein, & Lassonde, 1992), and the CUD of split-brain individuals (following surgical section of the corpus callosum) has been found to be even longer, reaching up to 96 ms (Aglioti, Berlucchi, Pallini, Rossi, & Tassinari, 1993; Clarke & Zaidel, 1989). Partial split-brain individuals have generally been reported to exhibit a CUD that is smaller than total split-brain individuals and not larger than normal individuals (Corballis, Corballis, & Fabri, 2004). For instance, Iacoboni, Ptito, Weekes, and Zaidel (2000) tested a sample of split-brain individuals amongst which no partial split-brain individual had a CUD exceeding 10 ms whereas three total split-brain individuals out of four had a CUD exceeding 25 ms. Nevertheless, an enlarged CUD has also been reported for one partial split-brain individual who underwent an anterior section (Di Stefano, Sauerwein, & Lassonde, 1992) and one partial split-brain who underwent a posterior section (Corballis et al., 2004). Based on these findings, it appears that the increased CUD, at least for total split-brain

individuals, results from disruption of callosal transfer, which necessitates reliance on alternative, slower, interhemispheric pathways.

Very few CUD studies have focused on bimanual responses and the role of the corpus callosum on the CUD for bimanual responses is not well understood. On the one hand, involvement of both hands in the response eliminates the unilateral motor preparation advantage that usually results from consistent initiation of the response by a single hemisphere. On the other hand, bimanual responses have been found to decrease the CUD as a consequence of slower uncrossed RTs (Berlucchi, Aglioti, Marzi, & Tassinari, 1995). For that reason, the bimanual CUD has sometimes been described as an inaccurate estimate of interhemispheric transfer time (Zaidel & Iacoboni, 2003).

A study compared the CUD elicited by key-pressing responses made unilaterally or bilaterally in normal individuals (Di Stefano, Morelli, Marzi, & Berlucchi, 1980). In the unimanual condition, ipsilateral and contralateral responses significantly differed only in the right visual field (RVF) whereas no significant difference was found in either visual field in the bimanual condition. On average, the CUD recorded from bimanual responses was smaller (0.71 ms) than the CUD recorded from unimanual responses (2.24 ms).

Bimanual responses were also tested with patients showing a callosal defect. An individual with callosal agenesis, B.F., showed a reduced bimanual CUD (8.0 ms)

compared to a unimanual CUD (12.6 ms) when responses were collected through release of a key. Also, Aglioti and collaborators (1993) compared the unimanual and bimanual CUD of one total split-brain individual (M.E.). M.E. yielded a larger CUD in the unimanual condition (69.6 ms) than in the bimanual condition (37.9 ms). This difference was attributed to a lengthening of ipsilateral RTs in the bimanual condition.

It remains that too little information has been gathered on the bimanual CUD of callosotomized (split-brain) individuals to be able to draw strong conclusions about the mechanisms involved. One goal of the present paper is therefore to provide a thorough analysis of the bimanual CUD, with data gathered from partial split-brain, total split-brain, and normal individuals. An asynchrony measure will also be used in order to disentangle the mechanism underlying the CUD recorded bimanually from that underlying synchronization between hands.

BIMANUAL COORDINATION

Investigation of bimanual coordination also provides information on interhemispheric transfer. The information pertaining to manual synchrony, just like the information giving rise to the CUD, is thought to transfer through the corpus callosum. Consequently, split-brain individuals should show impaired performance in tasks requiring bimanual coordination. Surprisingly, this has not consistently been observed.

For instance, callosotomized individuals showed strong coupling mechanisms for bimanual movements in tasks requiring rhythmic movement patterns between the hands (Tuller & Kelso, 1989). Also, it has been suggested that split-brain individuals differ from normal individuals with respect to spatial coupling (e.g., concurrent drawing of different forms by both hands) but not temporal coupling (Franz, Eliassen, Ivry, & Gazzaniga, 1996).

Data supporting deterioration of fine temporal bimanual skills following callosotomy have also been gathered (Diedrichsen, Hazeltine, Nurss, & Ivry, 2003; Eliassen, Baynes, & Gazzaniga, 2000; Preilowski, 1972). For instance, four split-brain patients, including one tested pre- and post-surgery (V. J.), were tested with a bimanual synchronization task where responses were either initiated in a self-paced fashion or triggered by visual stimuli (Eliassen et al., 2000). It was found that bimanual button presses were generally less synchronous for split-brain individuals as compared to normal and epileptic control subjects. Moreover, V. J. showed different synchrony at each stage of the callosotomy. Before the surgery, this patient showed no synchrony difference between self-paced or visually-triggered bimanual responses. After the anterior callosotomy, V. J. exhibited lower synchrony for self-paced responses as compared to visually-triggered responses. After the posterior section, no difference between the two conditions was found. This result was interpreted as evidence that the anterior and posterior portions of the corpus callosum are involved in different aspects of bimanual coordination. Specifically, it

was speculated that the anterior portion coordinates timing in relation to internal cues (e.g., self-paced responses) whereas the posterior portion coordinates timing in relation to external cues (e.g., visual stimuli).

In the present study, given that both the CUD and the synchrony of bimanual responses depend on callosal transfer, our prediction is that split-brain individuals should show increased CUDs and increased asynchrony values compared to normal individuals. Also, a comparison between anterior- and totally- split-brain individuals will be carried out. If the information giving rise to the CUD, or contributing to synchronization of the hands, transfers predominantly through the posterior portion of the corpus callosum, partial split-brain individuals should differ from total split-brain individuals on both measures. Alternatively, if the information giving rise to the CUD, or that contributing to synchronization of the hands, transfers predominantly through the anterior portion of the corpus callosum, partial split-brain individuals should differ from normal individuals on both measures.

DOES THE CUD RESULT FROM THE TRANSFER OF SENSORY OR MOTOR INFORMATION?

Several studies have addressed the issue of whether the CUD occurs at a sensory or motor level. For normal individuals, evidence has been gathered to support a motor locus. This claim comes from the inefficiency of visual parameters, such as manipulations of luminance or eccentricity, to affect the magnitude of the CUD (Clarke & Zaidel, 1989; Forster & Corballis, 1998; Roser & Corballis, 2002). In

contrast, manipulations of motor variables, such as alternating response fingers and using bimanual responses, did affect the CUD. The absence of CUD modulation by sensory manipulations along with the successful CUD modulation by motor manipulations suggests that this phenomenon arises at a motor level in normal individuals.

In callosotomized individuals, investigations of sensory and motor manipulations on the CUD have led to mixed results. For instance, a study with four total split-brain individuals revealed that manipulation of eccentricity affected the CUD of two of these individuals whereas manipulation of light intensity did not significantly impact the CUD of any of them (Clarke & Zaidel, 1989). The CUD of split-brain individuals was therefore interpreted as arising from interhemispheric pathways sensitive to eccentricity but not light intensity. Manipulation of motor parameters was also assessed for callosotomized individuals. For instance, increasing the complexity of the response, by alternating the responding fingers, did not modulate the CUD for one partial split-brain and two total split-brain individuals (Iacoboni & Zaidel, 1995).

Another goal of our study was to investigate the locus of the CUD for split-brain individuals. By varying visual features that predominantly recruited cortical (colour or motion stimuli) or subcortical (luminance stimuli) pathways, we targeted feature characteristics that should be differentially sensitive to the interhemispheric transfer taking place in groups exhibiting different levels of cortical connectivity. Our

prediction was that the CUD of total split-brain individuals should be more sensitive to manipulations of visual parameters than that of partial split-brain and normal individuals. Specifically, total split-brain individuals, in whom interhemispheric transfer is believed to take place at a subcortical level, which presumably only transfers certain feature types (i.e., luminance, but not colour or motion), should exhibit a CUD that is much larger and more sensitive to sensory manipulations than that of partial split-brain and normal individuals. In turn, partial split-brain individuals, whose CUD supposedly arises at a sensory level as a consequence of the anterior sectioning of the corpus callosum, should not necessarily be sensitive to visual feature manipulations. In this case, the rationale is that all types of visual information freely circulate across hemispheres through the posterior portion of the corpus callosum, and are therefore processed at a cortical level, which makes it unlikely that varying feature types will differentially impact on the CUD.

THE EFFECT OF ATTENTIONAL FACTORS ON THE CUD

Attentional manipulations can also affect the CUD. One example of such a manipulation involved presenting stimuli in locations that were predictable (stimuli consistently appearing on the same side) or unpredictable (stimuli randomly appearing to the left or right of fixation) in order to assess the impact of foreknowledge of the side of presentation in a total split-brain patient, M.E. (Aglioti et al., 1993). Averaged across eccentricities, it was reported that the CUD of M.E. was much larger in the unpredictable (130.4 ms) than in the predictable (30 ms)

conditions. The interpretation of this finding was difficult, however, because this difference was only found in the left visual field (LVF). Moreover, methodological limitations further tangled the interpretation of this result. In fact, the attentional factor was manipulated in such a way that two variables were confounded. Specifically, three levels of eccentricity (10°, 35°, or 70° of visual angle) and two types of presentation (predictable vs. unpredictable- referred to as random vs. blocked in the original paper) were used. At a given eccentricity, on any given predictable location trial, M.E. only had to monitor one spatial location, whereas on any given unpredictable location trial, M.E. had to monitor two spatial locations. Hence, the number of monitored spatial locations was confounded with the side predictability manipulation. It was therefore relevant to separate these two effects by controlling for the number of spatial locations. Our study addressed this issue by keeping the number of monitored spatial locations constant while solely varying the unpredictable (interhemispheric) versus predictable (intrahemispheric) presentation.

Finally, amongst our total split-brain group, one patient (D.D.V.) displayed left visual field extinction. This patient has shown failure to respond to LVF stimuli in the past as well as a strong rightward bias in line bisection (Corballis, Corballis, Fabri, Paggi, & Manzoni, 2005; Hausmann, Corballis, & Fabri, 2003). In this context, although it was not an *a priori* goal of this study, it was deemed relevant to interpret D.D.V.'s data in the light of theories of distribution of attention via the corpus callosum.

METHODS

Data used for this study were previously used for studying the redundant target effect (RTE ; Ouimet et al., 2009). In the present paper, a subset of these data, including only lateralised single-stimulus trials, was initially used to study the bimanual CUD. Then, as a second step, the entire data set was used to study bimanual asynchrony, this time adding stimuli presented on the vertical meridian as well as redundant trials.

PARTICIPANTS

Eight split-brain individuals and ten neurologically-intact individuals took part in this study. Amongst the patients, four had undergone complete callosotomy (M.L., F.B., D.D.V., & I.C.), and the other four had undergone a partial callosotomy (P.M., A.P., G.S., & M.M.) in order to limit the spread of epileptic seizures. In the total split-brain group, D.D.V. displayed left visual field extinction. Therefore, only stimuli presented in the right visual field were included in the analysis for this patient. In the partial split-brain group, all patients had undergone an anterior three-quarters section of the corpus callosum, except for G.S. who had undergone an anterior four-fifths section of the corpus callosum. All patients were treated with anticonvulsive medication at the time of testing. All participants had normal or corrected-to-normal vision and gave informed consent prior to their participation.

STIMULI

Stimuli were disks that occupied 2° of visual angle positioned around a fixation cross centrally located on the screen. Six equicentric stimulus positions about fixation were distributed around an imaginary circle (Figure 1A). Peripheral stimuli appeared at an eccentricity of 5° of visual angle from the left or right of fixation. Across all conditions, data gathered for the CUD were only collected from the four lateral locations whereas data gathered for the asynchrony measure were collected from the six possible locations as illustrated in Figure 1A.

----------Insert Figure 1 about here ----------

The feature defining the stimuli was an independent variable with three levels. Stimuli were either defined by luminance (white disks: luminance= 14.7 cd/m^2, CIE, xy coordinates: x=.285, y=.297 – on a black background: 0.1 cd/m^2, x=.368, y=.315), colour (green disks: x=.295, y=.561 – on an equiluminant grey background: 16.5 cd/m^2, x=.281, y=.291), or motion (small dots moving with a 100% coherent motion in an upward direction on a background of randomly positioned motionless dots: 1.0 cd/m^2, x=.284, y=.313). All stimuli involved onset detection. In the colour condition, equiluminance of stimuli with the background was obtained by the use of a flicker adjusted by participants for all six positions. In the motion condition, randomly positioned dots were first displayed on the screen and after an averaged

interval of 500 ms, dots composing the stimuli started to move coherently in an upward direction, such as the resulting stimulus was a disk that could only be defined by motion. In all conditions, contour detection was prevented by applying Gaussian filters on the disks.

Presentation type was another independent variable with two levels for the CUD and three levels for the asynchrony measure. For both measures, stimuli were either presented within an interhemispheric or an intrahemispheric block as illustrated in Figure 1B. For the asynchrony measure, stimuli could also be presented on the vertical midline. In the interhemispheric block, stimuli could appear equally often to the left or right of fixation in the upper hemifield in one block or in the lower hemifield in another block. Thus, in any given interhemispheric block, the stimulus could appear at one of two locations. In the intrahemispheric block, stimuli could only appear either to the left or right of fixation for the whole duration of the block. As in interhemispheric blocks, there were two possible locations, but in this case they were both within the same left or right hemifield. This manipulation therefore provided information on the effect of foreknowledge of the side versus vertical position. Specifically, interhemispheric blocks provided predictive information in one dimension (up/down) but not the other (left/right), whereas intrahemispheric blocks provided left/right but not up/down foreknowledge. Finally, only for the asynchrony measure, midline blocks were also included, which entailed two possible locations on the vertical meridian, one located in the upper visual field and one located in the lower visual field. Across all conditions, in order to increase the

number of trials per condition, the upper/lower visual field manipulation was not considered in the present experiment. Consequently, upper and lower stimuli were pooled across the other factors.

Manipulations were administered in a blocked fashion, yielding the following six conditions for the CUD: luminance-inter, luminance-intra, colour-inter, colour-intra, motion-inter, motion-intra, to which were added luminance-midline, colour-midline, and motion-midline for the asynchrony measure. Each block was composed of 30 catch-trials, 60 single-stimulus trials, and 30 redundant-stimulus trials. In a given block, single-stimulus trials equally appeared on the left vs. right side, or in the upper vs. lower visual field depending on the presentation type. For the purpose of the CUD, only RTs to lateralised single-stimulus trials were investigated. For the asynchrony measure, redundant-stimulus trials were also investigated. In this case, two stimuli were simultaneously presented as a function of the different presentation types as illustrated in Figure 1B.

The initial experimental design included the same number of blocks for split-brain and normal individuals but the number of blocks had to be reduced in order to ensure vigilance throughout testing for patients. Amongst split-brain individuals, M.L., and P.M., provided more trials than the other patients because they were tested before the number of trials was adjusted.

Each inter- or intra-hemispheric presentation type was respectively tested two or four times for each feature type (luminance, colour, or motion) for split-brain and normal individuals. Specifically, for split-brain individuals, every feature type was tested in one interhemispheric block with disks presented in the upper visual field and in one interhemispheric block with disks presented in the lower visual field. Normal individuals were tested with two interhemispheric blocks in each hemifield (above vs. below fixation). Also, for split-brain individuals, every feature type was tested in one intrahemispheric block with disks presented in the right visual field and in one intrahemispheric block with disks in the left visual field. Normal individuals were tested with two intrahemispheric blocks in each hemifield (left vs. right). For the midline presentation type, split-brain and normal individuals were tested with two blocks for each feature type except for two split-brain individuals (F.B. and A.P.) who were only tested with one midline block.

One practice block of forty trials was administered before the experimental blocks and six practice trials were presented before each block. Block order was counterbalanced across participants. Fixation was monitored and trials with eye movements were rejected.

PROCEDURE

Each participant was seated 40 cm in front of the computer screen. Each trial began with a fixation point that participants were instructed to fixate throughout the whole

duration of a trial. It stayed on the screen for an average interval of 500 ms, with this duration varying randomly between 400 ms and 600 ms from trial to trial in order to reduce the number of anticipation responses. Then, one disk was presented for 200 ms while the fixation point was still displayed on the screen. Participants were allowed a duration of 1000 ms to press the response keys in a simple RT task. As soon as a response was recorded, the fixation cross disappeared and there was a 1000 ms inter-trial interval (ITI). In catch trials (zero disks), to prevent participants from having to wait for two seconds before the next trial began, the average RT for the trials in which stimuli appeared was calculated and the duration of the response recording interval was adjusted to match the average RT.

Participants responded bimanually by pressing the "Z" key with their left index finger and the "M" key with their right index finger, at the same time, as soon as they perceived any disk. Two responses per trial were therefore collected, one for the left hand and one for the right hand.

RESULTS

Single-stimulus trials in the inter- or intra-hemispheric conditions were used for the CUD and the RTs analysis (this latter analysis is presented in Appendix 1, given that it is partially redundant with the CUD and asynchrony results). Asynchrony analyses relied on this former set of data but also included stimuli presented on the vertical meridian and redundant trials of inter-, intra-hemispheric, and midline conditions.

All analyses relied on a mixed model ANOVA. Bonferroni corrections were applied to multiple comparisons.

For all analyses, trials in which only one hand made a response were discarded and outliers were removed based on the Van Selst and Jolicœur (1994) method. Also, RTs shorter than 150 ms were considered anticipatory and removed from the analyses. Lateralised single-stimulus trials directly activated only one hemisphere, which can lead to a larger number of omissions for split-brain individuals. Patterns of exclusions were therefore investigated for these trials. On average, 30% of trials for total split-brain individuals, 18% of trials for partial split-brain individuals, and 9% of trials for normal individuals were excluded from the total number of single-stimulus trials. Table I shows a breakdown of excluded trials into eye movements, anticipations, omissions, one-hand responses, and outliers for each split-brain individually and for the normal individuals group. The exclusion rate for normal individuals was artificially inflated as a consequence of several one-hand responses by one participant who moved one of his index fingers along the keyboard and responded with the wrong key for several trials, therefore yielding an unusual number of one-hand responses. Nevertheless, enough trials were collected for this participant to be included in the sample. Also, the inflated percentage of excluded trials for partial and total split-brain individuals was mainly due to a larger proportion of omissions and one-hand responses as compared to normal individuals.

----------Insert Table I about here ----------

Note also that the total split-brain patient D.D.V. displayed left visual field extinction. Consequently, RTs are only reported for trials in which the stimulus was presented in the right visual field, hence leading to an absence of RTs for left visual field trials. D.D.V.'s results are displayed in the tables but were not included in the statistical analyses for reasons discussed later. Instead, his results are interpreted separately, leaving the total split-brain group with three patients.

CUD

Because the responses were bimanual, the CUD was computed for each trial by subtracting the RT for the hand on the same side as the stimulus from the RT for the hand on the opposite side. Overall mean CUD values for each split-brain patient and for the group of normal individuals are presented in Table II. For further reference, mean RTs and standard deviations for lateralised single-stimulus trials are reported in Table III.

----------Insert Tables II & III about here ----------

An ANOVA was run on the CUD using group (normals, partial SBs, total SBs) as a between-subjects factor and feature type (luminance, colour, motion), and presentation type (interhemispheric, intrahemispheric) as within-subjects factors. Main effects of group, $F(2, 14) = 21.4$, $MSE = 129.8$, $p < .001$, and feature type, $F(2,$

28) = 4.2, *MSE* = 45.1, $p < .03$, were found. The main effect of group was driven by the large CUD of total split-brain individuals (20.4 ms) which significantly exceeded that of partial split-brain (3.8 ms) and normal individuals (0.4 ms), both $p < .001$, which in turn did not differ, $p > .69$ (Fig. 2A). Decomposition of the main effect of feature type revealed a trend for the CUD elicited by colour stimuli (11.0 ms) to exceed the CUD elicited by motion stimuli (5.9 ms), $p > .074$ (Fig. 2B). The CUD elicited by luminance stimuli (7.8 ms) did not differ from any other feature type, both $p > .20$.

---------- Insert Figure 2 about here ----------

Significant two-ways interactions were also identified. Feature type and group interacted, $F(4, 28) = 3.1$, *MSE* = 45.1, $p < .035$. Specifically, for total split-brain individuals, the CUD elicited by colour stimuli (27.6 ms) significantly exceeded the CUD elicited by motion stimuli (13.3 ms), $p < .013$, but not by luminance stimuli (20.3 ms), $p > .14$, whereas partial split-brain (luminance: 2.8 ms, colour: 5.0 ms, motion: 3.7 ms) and normal individuals (luminance: 0.3 ms, colour: 0.2 ms, motion: 0.7 ms) showed no modulation of CUD as a function of feature type, all $p > .99$ (Fig. 2B).

ASYNCHRONY: ANALYSIS ON THE MEANS

The asynchrony measure was computed by using the absolute value of the difference between the left-hand RT and the right-hand RT on each trial, which was then averaged across trials. This provided a measure which, contrary to the CUD, did not specifically depend on the interaction between hand and visual field, but instead merely assessed the asynchrony between the two hands. This measure is intuitive and provides larger values when there are larger intervals between the two responses, regardless of the direction or consistency of those intervals. Asynchrony values and standard deviations for lateralised single-stimulus, midline and redundant trials for each split-brain individual and for the group of normal individuals are presented in Table IV.

This ANOVA was run using group (normals, partial SBs, total SBs) as a between-subjects factor and feature type (luminance, colour, motion), presentation type (interhemispheric, intrahemispheric, midline), and number of stimuli (one, two) as within-subjects factors. One goal of this analysis was to investigate the influence of one versus two directly activated hemispheres on response synchrony. Given that both hemispheres were directly activated by midline and interhemispheric redundant stimuli, these conditions were expected to produce less asynchrony than single-interhemispheric or intrahemispheric conditions, which directly activated only one hemisphere, at least for split-brain individuals. In this context, it was expected to find a presentation type X number of stimuli X group interaction.

----------Insert Table IV about here ----------

A main effect of group was found, $F(2, 14) = 23.6$, $MSE = 1742.2$, $p < .001$, indicating that bimanual coordination differed across groups (Fig. 3A). Multiple comparisons suggested responses for total split-brain individuals (53.7 ms) and partial split-brain individuals (39.6 ms) were less synchronous than those of normal individuals (13.6 ms), both $p < .002$. In turn, the asynchrony of the two split-brain groups did not differ, $p > .24$. A main effect of number of stimuli was also found, $F(1, 14) = 28.5$, $MSE = 14.9$, $p < .001$, due to the increased asynchrony of responses when one stimulus (37.0 ms) was presented as compared to two stimuli (34.3 ms) (Fig. 3A).

----------Insert Figure 3 about here ----------

Two-way interactions were found. Number of stimuli interacted with group, $F(2, 14) = 7.9$, $MSE = 14.9$, $p < .005$ (Fig. 3A). Partial (one: 41.0 ms, two: 38.2 ms) and total (one: 56.2 ms, two: 51.3 ms) split-brain individuals were more asynchronous when one stimulus was presented as compared to two stimuli, both $p < .009$, whereas normal individuals showed no such difference (one: 13.8 ms, two: 13.4 ms), $p > .52$. Also, number of stimuli interacted with presentation type, $F(2, 28) = 8.5$, $MSE = 27.3$, $p < .001$ (Fig. 3A). Participants were generally more asynchronous when one stimulus was presented as compared to two stimuli in the interhemispheric

(one: 38.6 ms, two: 33.0 ms) or the midline conditions (one: 36.0 ms, two: 32.4 ms), both $p < .002$, whereas there was no difference in the intrahemispheric condition (one: 36.3 ms, two: 37.5 ms), $p > .22$.

Interestingly, a three-way interaction involving number of stimuli, presentation type, and group was found, $F(4, 28) = 4.3$, $MSE = 27.3$, $p < .009$ (Fig. 3A). Total split-brain individuals were more asynchronous when one stimulus was presented as compared to two stimuli in the interhemispheric (one: 60.7 ms, two: 48.4 ms) or the midline conditions (one: 53.2 ms, two: 47.2 ms), both $p < .008$, whereas there was no difference in the intrahemispheric condition (one: 54.7 ms, two: 58.2 ms), $p > .08$. In turn, partial split-brain individuals were more asynchronous when one stimulus was presented as compared to two stimuli only in the midline condition (one: 41.2 ms, two: 36.6 ms), $p < .017$, whereas there was no difference in the interhemispheric (one: 41.6 ms, two: 37.7 ms) or intrahemispheric condition (one: 40.1 ms, two: 40.4 ms), both $p > .11$. Finally, normal individuals did not exhibit any asynchrony difference between one and two stimuli as a function of inter- (one: 13.5 ms, two: 13.0 ms), intra-hemispheric (one: 14.1 ms, two: 13.8 ms), or midline conditions (one: 13.7 ms, two: 13.5 ms), all $p > .73$. Finally, a group, feature type, and number of stimuli interaction was found, $F(4, 28) = 2.9$, $MSE = 9.5$, $p < .044$ (Fig. 3B). Total split-brain individuals were at least marginally more asynchronous when one stimulus was presented as compared to two stimuli in the colour (one: 56.6 ms, two: 48.0 ms), $p < .001$, and luminance conditions (one: 54.4 ms, two: 50.4 ms), $p < .058$, whereas no significant difference was found in the motion condition

(one: 57.5 ms, two: 55.4 ms), $p > .26$. In turn, partial split-brain individuals were at least marginally more asynchronous when one stimulus was presented as compared to two stimuli for all feature types, namely colour (one: 36.4 ms, two: 34.9 ms), $p < .001$, luminance (one: 44.8 ms, two: 41.2 ms), $p < .048$, and motion (one: 41.8 ms, two: 38.7 ms), $p < .070$. Finally, normal individuals did not show any synchrony difference for one versus two stimuli for any feature type, namely colour (one: 13.3 ms, two: 12.9 ms), luminance (one: 14.3 ms, two: 13.8 ms), and motion (one: 13.7 ms, two: 13.5 ms), all $p > .17$.

Asynchrony: Analysis on the variability

The asynchrony measure used in the previous section is limited in that 1) it can be sensitive to consistent between-hand differences that do not necessarily reflect interhemispheric coordination and 2) it can be partially confounded with the CUD, tending to increase with CUD. Therefore, the present section addresses these issues by using the variability of bimanual asynchrony, a measure that is not sensitive to the aforementioned problems. In order to capture optimally the extent to which RTs varied across hands on a given trial, a difference score was calculated by subtracting the right-hand RT from the left-hand RT, this time keeping the sign (positive or negative) that defined the relationship. As a result, negative and positive values were obtained for the between-hand differences depending on which hand had first pressed the response key. Outliers on these values were removed by using the Van Selst and Jolicœur (1994) method. The variance of this asynchrony measure was

calculated and log-transformed (using the natural log) for each condition in order to normalize the distribution. The log-transformed variance of asynchrony was then submitted to an ANOVA with the between-subjects factor group (normals, partial SBs, total SBs), and the within-subjects factors feature type (luminance, colour, motion), presentation type (interhemispheric, intrahemispheric, midline), and number of stimuli (one, two). In order to facilitate the interpretation of the results, the means of the log-transformed variances were converted to their original scale (i.e., exponentiated) and their square roots were then calculated, yielding the mean standard deviations of asynchrony values that are presented in Table V and in Figure 4.

----------Insert Table V and Figure 4 about here ----------

A main effect of group was found, $F(2, 14) = 36.2$, $MSE = 4.1$, $p < .001$, indicating that the variability of asynchrony differed across groups (Fig. 4A). Multiple comparisons suggested that total split-brain (7.88) and partial split-brain (6.47) individuals were more variable than normal individuals (5.29), both $p < .003$. In turn, total split-brain individuals were more variable than partial split-brain individuals, $p < .005$. A main effect of number of stimuli was also found, $F(1, 14) = 25.2$, $MSE = .05$, $p < .001$, due to the increased variability when one stimulus (6.62) was presented as compared to two stimuli (6.47) (Fig. 4A). A main effect of presentation type was also found, $F(2, 28) = 17.0$, $MSE = 0.18$, $p < .001$, due to the increased variability in the inter- (6.60) and intra-hemispheric (6.68) conditions as

compared to the midline condition (6.36), both $p < .004$ (Fig. 4A). In turn, the variability for the inter- and intra-hemispheric conditions did not differ, $p > .14$.

Number of stimuli interacted with group, $F(2, 14) = 4.2$, $MSE = 0.05$, $p < .04$ (Fig. 4A). Partial (one: 6.56, two: 6.38) and total (one: 7.99, two: 7.77) split-brain individuals were more variable when one stimulus was presented as compared to two stimuli, both $p < .004$, whereas normal individuals showed no such difference (one: 5.32, two: 5.27), $p > .20$. Group also interacted with presentation type, $F(4, 28) = 8.8$, $MSE = 0.18$, $p < .001$ (Fig. 4A). Total split-brain individuals were more variable when stimuli were presented in an inter- (8.05) or intra-hemispheric (8.18) fashion as compared to on the midline (7.40), both $p < .001$, whereas no difference was found for partial split-brain (inter: 6.47, intra: 6.54, midline: 6.39) and normal individuals (inter: 5.28, intra: 5.32, midline: 5.28), all $p > .82$. Presentation type also interacted with number of stimuli, $F(2, 28) = 7.3$, $MSE = .08$, $p < .003$ (Fig. 4A). In the interhemispheric condition, more variability was observed when one stimulus (6.77) was presented as compared to two stimuli (6.43), $p < .001$, whereas no such difference was observed for the intrahemispheric (one: 6.68, two: 6.68) and midline conditions (one: 6.41, two: 6.30), $p > .08$. Number of stimuli also interacted with feature type, $F(2, 28) = 5.7$, $MSE = .08$, $p < .009$ (Fig. 4B). The asynchrony was more variable when one stimulus (6.61) was presented as compared to two stimuli (6.28) in the colour condition, $p < .001$, whereas there was no such difference in the luminance (one: 6.57, two: 6.51) and motion conditions (one: 6.68, two: 6.62), both $p > .28$.

Finally, a three-way interaction involving number of stimuli, presentation type, and group was found, $F(4, 28) = 4.9$, $MSE = .09$, $p < .004$ (Fig. 4A). Total split-brain individuals were more variable when one stimulus was presented as compared to two stimuli in the interhemispheric condition (one: 8.40, two: 7.70 ms), $p < .001$, but not in the midline condition (one: 7.51, two: 7.29 ms), $p > .091$, and were less variable when one stimulus was presented as compared to two stimuli in the intrahemispheric condition (one: 8.05, two: 8.31 ms), $p < .02$. In turn, partial split-brain individuals were more variable when one stimulus (6.63) was presented as compared to two stimuli (6.44) in the intrahemispheric condition, $p < .05$, but no variability difference was observed between one versus two stimuli in the interhemispheric (one: 6.59, two: 6.36) or midline conditions (one: 6.46, two: 6.33), both $p > .10$. Finally, the variability of asynchrony of normal individuals was not influenced by the presentation of one versus two stimuli as a function of the interhemispheric (one: 5.33, two: 5.23), intrahemispheric (one: 5.35, two: 5.29), or midline conditions (one: 5.27, two: 5.30), all $p > .24$.

D.D.V.

For D.D.V., CUDs are reported in Table II, RTs in Table III, asynchrony means in Table IV, and log-transformed variance of asynchrony in Table V. As shown in Table II, he consistently exhibited the most extreme CUD values amongst split-brain individuals. Single-stimulus trials were only considered if presented on the midline

or in the RVF. Because of hemineglect, D.D.V. did not complete any intrahemispheric block with stimuli presented in the LVF. Nevertheless, interhemispheric blocks contained single-stimulus trials that were presented in the LVF. Amongst LVF trials, D.D.V. responded more frequently with his left hand as compared to his right hand. Distribution of omissions and hits for each hand for stimuli presented in the LVF of D.D.V. are displayed in Table VIA. Although most of these trials yielded omissions, a small number of responses to LVF stimuli were recorded from D.D.V. For trials that yielded at least a partial response when stimuli were presented in the LVF, mean RTs are reported in Table VIB for each hand as a function of the number of hands producing the response.

----------Insert Table VI about here ----------

DISCUSSION

We examined the bimanually-recorded CUD and the level of manual asynchrony exhibited by normal, partial split-brain, and total split-brain individuals. We found that the CUD of total split-brain individuals (20.8 ms) exceeded that of partial split-brain (3.8 ms) and normal (0.4 ms) individuals. In turn, the CUDs of partial split-brain and normal individuals did not differ.

An important distinction between our study and most previous studies investigating the CUD involved our use of bimanual responses. In fact, to the best of our

knowledge, ours is the first study to compare bimanually recorded CUD between partial and total split-brain individuals.

In a study by Di Stefano et al. (1980), a CUD averaging 0.71 ms was found in normal individuals when key-press responses were recorded bimanually, an estimate consistent with our own data. No data is available on the bimanual CUD of partial split-brain individuals, but studies investigating the unimanual CUD traditionally reported small values (but see Di Stefano, Sauerwein, & Lassonde, 1992, for an exception). For instance, a CUD of 5.8 ms was found for a partial split-brain patient with an anterior section of the corpus callosum when stimuli were presented at 4 degrees of eccentricity (Iacoboni, Fried, & Zaidel, 1994). In contrast, a CUD of up to 37.9 ms was found for a total split-brain patient when distal bilateral responses were recorded (Aglioti et al., 1993). Our data from total split-brain individuals **are** in line with this estimate. In the light of our results, it therefore appears that the bimanual CUD exhibits the same response pattern as for the unimanual CUD. In both cases, the means of the CUD sharply increase from normal individuals to total split-brain individuals, with partial split-brain individuals typically showing a CUD very close to the normal range.

A different pattern was observed for the asynchrony measure; the asynchrony means of both total (53.7 ms) and partial split-brain (39.6 ms) individuals exceeded that of normal individuals (13.6 ms). Similarly, both total and partial split-brain individuals showed increased variances of asynchrony compared to normal individuals. Also,

the asynchrony of total split-brain individuals was more variable than that of partial split-brain individuals, suggesting a further loss of bimanual coordination following a posterior section of the corpus callosum. This result is in line with the hypothesis that both the anterior and posterior portions of the corpus callosum transfer information relevant to bimanual coordination (Eliassen et al., 2000).

The CUD and asynchrony results taken together reflect an interesting dissociation for partial split-brain individuals relative to normal individuals. The fact that partial split-brain individuals exhibited an increased and more variable asynchrony along with a normal CUD relative to normal individuals suggests that two different mechanisms underlie these phenomena. The existence of independent mechanisms underlying the CUD and the asynchrony between hands is therefore postulated. Specifically, the information giving rise to each of these phenomena seemingly transfer through different callosal pathways. It is likely that our asynchrony measure reflects a synchronization mechanism that arises at a motor level more anterior, and/or extending less posteriorly through the corpus callosum, than the CUD. It is also proposed that disruption of this synchronization mechanism does not translate into modulation of the CUD because it conjointly affects crossed and uncrossed responses.

As expected, total split-brain individuals showed enlarged CUD as well as enlarged and more variable asynchrony values compared to normal individuals. In this case, the complete callosal section disrupted the transfer of information underlying both

the CUD and the asynchrony measure. Total split-brain individuals also showed more variable asynchrony compared to partial split-brain individuals. This suggests that the preserved splenium of partial split-brain individuals is more efficient to transfer interhemispheric information than the subcortical pathway through which information transfers in total split-brain individuals.

The idea of different processes underlying the CUD and the asynchrony is similar to that postulating independent processes for the CUD and the RTE (Corballis, 2002). Adding to this idea, we not only suggest that the process underlying the CUD is different from that underlying the RTE and the asynchrony, but we also suggest that a common process may underlie the latter two measures. Evidence for this suggestion comes from a comparison of the patterns exhibited by each group for the three measures, namely the CUD, the asynchrony, and the RTE. According to previously published results, the RTEs of both partial and total split-brain individuals were enhanced compared to that of normal individuals (Ouimet et al., 2009). In the present paper, this pattern was mimicked by the means and variability of asynchrony of partial and total split-brain individuals which significantly differed from those of normal individuals. However, a different pattern was obtained for the CUD, with partial split-brain individuals exhibiting a CUD within the normal range. In short, the pattern between groups was similar for the RTE and the asynchrony but different for the CUD. Specifically, patients lacking the anterior portion of the corpus callosum exhibited enhanced RTE and asynchrony values, but normal CUD values. In this context, the parallel modulation of the RTE and asynchrony measures

at the level of group means may suggest the existence of a common underlying process. In fact, our data show that increased interhemispheric interactions, as indexed by the enhanced RTE of split-brain individuals, can be associated with a loss of synchrony. We interpret this as evidence that the enhanced RTE of split-brain individuals results from interruption of motor transfer, consistent with the hemispheric coactivation model (Miller, 2004).

BIMANUAL COORDINATION

This paper also addressed the question of whether direct activation of two hemispheres, instead of only one, contributes to an increased synchrony for split-brain individuals relative to normal individuals. In our study, total split-brain individuals showed reduced and less variable asynchrony when redundant stimuli were presented relative to single stimuli in the interhemispheric condition, but did not show this pattern when stimuli were presented intrahemispherically. This result, along with the absence of such pattern for normal individuals, clearly demonstrates that split-brain individuals' synchrony deteriorates when only one hemisphere is activated as compared to two hemispheres. Our data therefore provide support for the claim that split-brain individuals exhibit specific impairments relative to temporal aspects of bimanual coordination. Furthermore, our results also support the view according to which an anterior section of the corpus callosum is sufficient to disrupt the transfer of information pertaining to bimanual coordination (Preilowski, 1972).

On the nature of the CUD

Our data also enabled us to shed some light on the nature of the CUD. In normal individuals, the CUD has traditionally been associated with transfer of motor information through fast callosal fibres. Anatomical support comes from studies on the distribution of callosal fibres. The callosal region connecting the motor areas is composed of fast-conducting, large-diameter, highly-myelinated fibres that can achieve an interhemispheric delay of only 3.25 ms (Aboitiz, Lopez, & Montiel, 2003), namely an estimate congruent with the normal CUD. Our data on normal individuals are also consistent with this estimate when taking into account that bimanual responses contribute to a reduction of the CUD.

As discussed in the Introduction, partial split-brain individuals have shown more variable results, sometimes ranging from practically normal CUDs (Berlucchi et al., 1995; Tassinari, Aglioti, Pallini, Berlucchi, & Rossi, 1994) to significantly lengthen ones (Di Stefano et al., 1992; Corballis et al., 2004). Our data suggest that the CUD of partial split-brain individuals who underwent an anterior section indeed falls within the normal range. This implies that sectioning the anterior portion of the corpus callosum is not sufficient to disrupt significantly the exchange of information giving rise to the CUD. In this context, it appears likely that both the anterior and posterior callosal regions can subserve a speeded integration of information across hemispheres.

In that regard, Berlucchi et al. (1995) suggested that fast crossed visuomotor responses to lateralised stimuli can be mediated by all portions of the corpus callosum. This idea is consistent with Clarke and Zaidel's model (1989) according to which parallel processing can take place simultaneously in all possible routes, either motor, visual, or subcortical, and can result in a race between the different pathways. Our results are also consistent with the idea that fast callosal motor fibres may contribute to the transfer of information pertaining to the CUD for normal individuals whereas transfer may rely on slightly slower, callosal sensory pathways for partial split-brain individuals. In other words, the proportion of sensory fibres contributing to the CUD is likely to increase gradually from normal to partial split-brain individuals. In turn, total split-brain individuals showed the largest CUD given no motor or sensory input was transferred through the corpus callosum. Consequently, information had to transfer through slow, subcortical pathways sensitive to sensory manipulations.

In our study, further support for the idea of a graded sensory contribution to the CUD comes from G.S.'s data. Although this observation may be anecdotal, it is relevant to underline that G.S., the partial split-brain patient with the most extensive callosal section, consistently exhibited the highest CUD values in the interhemispheric condition, namely the condition that necessitated the highest level of interhemispheric integration (see Table 2). We therefore speculate that transfer of information giving rise to the CUD extends over a widely spread callosal region and

that a more extensive section may be correlated with an increased CUD. In order to test this hypothesis thoroughly, correlation analyses involving many different extents of callosal sections would be necessary.

MANIPULATIONS OF FEATURE TYPE ON THE CUD

The manipulation of feature type on the CUD also provided information pertaining to the nature of the CUD. For normal individuals, our findings support what has been consistently reported regarding such manipulations, namely that sensory manipulations generally fail to translate into differential CUDs (Forster & Corballis, 1998).

For partial split-brain patients, given their splenium was preserved, it was hypothesized that visual information could cross freely between hemispheres and that manipulation of visual parameters should not affect the CUD. Our data supported this prediction because these patients did not show differential CUDs as a function of feature type (luminance: 2.8 ms, colour: 5.0 ms, motion: 3.7 ms). This result contrasts with the enhanced CUD reported in one partial split-brain individual following a visual (eccentricity) manipulation (Iacoboni et al., 1994). In this study, the CUD averaged 5.8 ms when stimuli were presented at 4 degrees of eccentricity compared to 20.6 ms when stimuli were presented at 8 degrees of eccentricity (Iacoboni et al., 1994). We have no obvious explanation for this seeming contradiction involving visual manipulations other than the possibility that the CUD

of partial split-brain individuals is sensitive to manipulations of only certain visual properties, such as eccentricity, but insensitive to others such as the ones used in our study.

Finally, total split-brain patients proved sensitive to our visual feature manipulation by exhibiting a larger CUD when stimuli were defined by colour (27.6 ms) compared to motion (13.3 ms). On an individual basis, this pattern was found in three out of four total split-brain individuals, M.L. being the only exception with a motion CUD exceeding his colour CUD. We interpret the group finding as evidence that the CUD of total split-brain individuals is sensitive to visual manipulations, but a finer interpretation of the colour versus motion difference remains speculative. One difficulty comes from the fact that our motion stimuli were confounded by local luminance changes and did not isolate cortical processing like equiluminant colour stimuli. For this reason, we cannot unequivocally refute the possibility that our motion stimuli were processed subcortically. Subcortical contributions have been associated with certain types of motion processing (Naikar, 1996; Cavanagh, 1992). In fact, there is evidence that interhemispheric integration of some low-level motion information can occur subcortically via an attention-based motion process (Cavanagh, 1992). In this context, an enhanced CUD for colour stimuli compared to motion stimuli would be reconcilable with the idea of a lengthy interhemispheric transfer of cortical (colour) information compared to faster interhemispheric transfer of subcortical (motion) information for total split-brain individuals. Nevertheless,

this result remains ambiguous given that luminance stimuli failed to produce a different CUD compared to colour or motion stimuli.

Effects of attentional factors on the CUD

Very few studies have investigated the effect of spatial uncertainty on the CUD. As mentioned in the Introduction, Aglioti and colleagues (1993) tested M.E., a total split-brain individual who shows a right prefrontal lesion but otherwise spared premotor and motor cortices. In their study, it was reported that M.E. exhibited an enhanced CUD when the side of presentation was unpredictable as compared to when the side of presentation was predictable. Our data showed contrasting results, namely an absence of a side predictability effect (inter- vs. intra-hemispheric presentation, in our case). In the Introduction, we pointed out a potential ambiguity in their design that could account for the discrepant results, namely that the number of monitored spatial locations was confounded with the side predictability manipulation in Aglioti et al.'s study.

Moreover, it is noteworthy that the CUD values exhibited by M.E. (random: 130.4 ms, blocked: 30 ms) closely resembled those of D.D.V. (random: 134.3 ms, blocked: 46.6 ms), who was our total split-brain individual displaying left visual field extinction. Moreover, M.E. exhibited extinction in his left visual field during practice trials (although this tendency was overcome during experimental trials) (Aglioti et al., 1993). It is therefore questionable whether M.E.'s results reflected a

pattern usually exhibited by total split-brain individuals or merely an abnormal functioning of the right hemisphere.

In this context, it appears relevant to analyse further D.D.V.'s data. In the present study, D.D.V. was not included in the group analysis because 1) he almost always missed LVF stimuli and 2) his LVF extinction could have interacted differently with the CUD as compared to other total split-brain individuals. D.D.V. has in fact been described as exhibiting "unusual hemineglect" (Corballis et al., 2005) which further motivated our decision to proceed to an individual interpretation of his results.

An assessment of D.D.V.'s case based on the hemispheric coactivation model (Miller, 2004) is useful to understand the differences that may underlie D.D.V.'s CUD as compared to the CUD of other total split-brain individuals. The graded hemispheric coactivation model assumes that both hemispheres contribute to some extent to the initiation of a response, but that a stronger influence is exerted by the hemisphere contralateral to the responding hand. This model suggests that two factors affect the size of the CUD, namely 1) the difference between within- and between-hemisphere transmission signals from sensory areas and motor areas and 2) the respective contribution of the ipsilateral and contralateral hemispheres to the initiation of the motor response. In the light of these two factors, we formulate the following remarks. In regard to the first factor affecting the size of the CUD, it cannot be ruled out that D.D.V. did not differ from other split-brain individuals on the basis of within-hemisphere processing. Specifically, his left visual field

extinction raised doubts regarding potential right hemisphere damage. Such lateralised damage could have created a within-hemisphere processing imbalance across hemispheres for D.D.V. that was not present for other split-brain individuals, which could have accounted for differential CUDs. Moreover, because the CUD of D.D.V. was calculated differently than that of other split-brain individuals, further differences between CUDs could have arisen. Specifically, for D.D.V., right-hand responses always constituted ipsilateral responses and left-hand responses always constituted contralateral responses. Contrary to the calculation used for the CUD of other individuals, no counterbalancing between left/right hands and ipsi-/contra-lateral could be done. D.D.V.'s CUD therefore only reflected one direction of transfer, indexed by a left-hand minus right-hand subtraction. According to Miller's model, the hemisphere contralateral to the responding hand exerts more control over the response initiation than the ipsilateral hemisphere. In this context, D.D.V.'s left (normally-functioning) hemisphere may have exerted more control over all uncrossed responses, whereas his right (potentially damaged) hemisphere may have exerted more control over all crossed responses, this functional difference between hemispheres possibly adding to the CUD magnitude. In short, the extreme CUD values exhibited by D.D.V. may not only have reflected lengthy interhemispheric transfer but may have also reflected right hemisphere damage. Consequently, it was justified to interpret his data individually.

An alternative, non-mutually exclusive, explanation for the very large CUD exhibited by D.D.V. relies on the hypothesis of attentional imbalance following

callosotomy. According to this view, sectioning the corpus callosum can result in destabilization of hemispheric balance from which attentional disparities between hemispheres can ensue (Kinsbourne, 2003). The interpretation of D.D.V.'s results remains tentative and context-specific, because he has exhibited intermittent hemineglect depending on the task at hand. For instance, his hemineglect remained undetected with an RTE paradigm using guide-boxes before the appearance of stimuli (Savazzi & Marzi, 2004) or with a visual illusion requiring interhemispheric integration (Corballis, Barnett, Fabri, Paggi, & Corballis, 2004), whereas it was apparent, or at least intermittent, in other tasks using simple RTs or line bisection (Corballis, Corballis, Fabri, Paggi, & Manzoni, 2005; Hausmann, Corballis, & Fabri, 2003). More investigation is therefore necessary to document further the occurrence of left visual field extinction in split-brain individuals and understand its impact on the CUD.

CONCLUSION

Our study sheds light on disruption of callosal transfer occurring in partial and total split-brain individuals compared to normal individuals. Specifically, total split-brain individuals, but not partial split-brain individuals, showed a larger CUD than normal individuals, whereas both split-brain groups were less synchronous than normal individuals. This provided behavioural evidence implicating the corpus callosum in the transfer of information pertaining to the bimanual CUD and the synchronization of the hands, although the information underlying each of these phenomena

seemingly transfers through different callosal pathways. The synchronization mechanism appears to arise at a motor level more anterior, and/or that extends less posteriorly through the corpus callosum, than the CUD. Additional research is needed to support this suggestion and refine our functional understanding of callosal connections.

REFERENCES

Aboitiz, F., Lopez, J., & Montiel, J. (2003). Long distance communication in the human brain: timing constraints for inter-hemispheric synchrony and the origin of brain lateralization. *Biol Res, 36*, 89-99.

Aglioti, S., Berlucchi, G., Pallini, R., Rossi, G. F., & Tassinari, G. (1993). Hemispheric control of unilateral and bilateral responses to lateralized light stimuli after callosotomy and in callosal agenesis. *Experimental Brain Research, 95*, 151-165.

Bashore, T. R. (1981). Vocal and manual reaction time estimates of interhemispheric transmission time. *Psychological Bulletin, 89*, 352-368.

Berlucchi, G., Aglioti, S., Marzi, C. A., & Tassinari, G. (1995). Corpus callosum and simple visuomotor integration. *Neuropsychologia, 33*(8), 923-936.

Cavanagh, P. (1992). Attention-based motion perception. *Science, 257*, 1563-1565.

Clarke, J. M., & Zaidel, E. (1989). Simple reaction times to lateralized light flashes. *Brain, 112*, 849-870.

Corballis, M. C. (2002). Hemispheric interactions in simple reaction time. *Neuropsychologia, 40*, 423-434.

Corballis, M. C., Barnett, K. J., Fabri, M., Paggi, A., & Corballis, P. M. (2004). Hemispheric integration and differences in perception of a line-motion illusion in the divided brain. *Neuropsychologia, 42*, 1852-1857.

Corballis, M. C., Corballis, P. M., & Fabri, M. (2004). Redundancy gain in simple reaction time following partial and complete callosotomy. *Neuropsychologia, 42*, 71-81.

Corballis, M. C., Corballis, P. M., Fabri, M., Paggi, A., & Manzoni, T. (2005). Now you see it, now you don't: Variable hemineglect in a commissurotomized man. *Cognitive Brain Research, 25*, 521-530.

Di Stefano, M., Morelli, M., Marzi, C. A., & Berlucchi, G. (1980). Hemispheric control of unilateral and bilateral movements of proximal and distal parts of the arm as inferred from simple reaction time to lateralized light stimuli in man. *Experimental Brain Research, 38*, 197-204.

Di Stefano, M., Sauerwein, H. C., & Lassonde, M. (1992). Influence of anatomical factors and spatial compatibility on the stimulus-response relationship in the absence if the corpus callosum. *Neuropsychologia, 30*(2), 177-185.

Diedrichsen, J., Hazeltine, E., Nurss, W. K., & Ivry, R. B. (2003). The role of the corpus callosum in the coupling of bimanual isometric force pulses. *J Neurophysiol, 90*, 2409-2418.

Eliassen, J. C., Baynes, K., & Gazzaniga, M. S. (2000). Anterior and posterior callosal contribution to simultaneous bimanual movements of the hands and fingers. *Brain, 123*, 2501-2511.

Forster, B., & Corballis, M. C. (1998). Interhemispheric transmission times in the presence and absence of the forebrain commissures: effects of luminance and equiluminance *Neuropsychologia, 36*(9), 925-934.

Franz, E. A., Eliassen, J. C., Ivry, R. B., & Gazzaniga, M. S. (1996). Dissociation of spatial and temporal coupling in the bimanual movements of callosotomy patients. *Psychological Science, 7*(5), 306-310.

Hausmann, M., Corballis, M. C., & Fabri, M. (2003). Line bisection in the split brain. *Neurospychology, 17*, 602-609.

Iacoboni, M., Fried, I., & Zaidel, E. (1994). Callosal transmission time before and after partial commissurotomy. *NeuroReport, 5*, 2521-2524.

Iacoboni, M., & Zaidel, E. (1995). Channels of the corpus callosum: Evidence from simple reaction times to lateralized flashes in the normal and the split-brain. *Brain, 118*, 779-788.

Kinsbourne, M. (2003). The corpus callosum equilibrates the cerebral hemispheres. In E. Zaidel & M. Iacoboni (Eds.), *The Parallel Brain: The cognitive neuroscience of the corpus callosum*. Cambridge: MIT Press.

Miller, J. (2004). Exaggerated redundancy gain in the split brain: A hemispheric coactivation account. *Cognitive Psychology, 49*, 118-154.

Milner, A. D., Jeeves, M. A., Silver, P. H., Lines, C. R., & Wilson, J. (1985). Reaction times to lateralized visual stimuli in callosal agenesis: stimulus and response factors. *Neuropsychologia, 23*(3), 323-331.

Naikar, N. (1996). Perception of apparent motion of colored stimuli after commissurotomy. *Neuropsychologia, 34*(11), 1041-1049.

Ouimet, C., Jolicoeur, P., Miller, J., Ptito, A., Paggi., A., Foschi, N., et al. (2009). Sensory and motor involvement in the enhanced redundant target effect: A study comparing anterior- and totally split-brain individuals. *Neuropsychologia, 47*, 684-692.

Preilowski, B. F. B. (1972). Possible contribution of the anterior forebrain commissures to bilateral motor coordination. *Neuropsychologia, 10*, 267-277.

Roser, M., & Corballis, M. C. (2002). Interhemispheric neural summation in the split brain with symmetrical and asymmetrical displays. *Neuropsychologia, 40*, 1300-1312.

Tassinari, G., Aglioti, S., Pallini, R., Berlucchi, G., & Rossi, G. F. (1994). Interhemispheric integration of simple visuomotor responses in patients with partial callosal defects. *Behavioural Brain Research, 64*, 141-149.

Tuller, B., & Kelso, J. A. S. (1989). Environmentally-specified patterns of movement coordination in normal and split-brain subjects. *Experimental Brain Research, 75*, 306-316.

Zaidel, E., & Iacoboni, M. (2003). Sensorimotor integration in the split-brain. In E. Zaidel & M. Iacoboni (Eds.), *The Parallel Brain: The cognitive neuroscience of the corpus callosum* (pp. 319-336). Cambridge: MIT Press.

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Table I. Percentage and total number of excluded trials for lateralised single-stimulus for each split-brain individual and average for the normal group. Breakdown of excluded trials into eye movements, anticipations, omissions, one-hand responses, and outliers.

		% of exclusion (excluded/total trials)	Reasons for exclusion				
			Eye mov.	Anticipations	Omissions	One hand	Outliers
Normals (n = 10)		9% (1257/14400)	2%	1%	2%	2%	2%
Partial SBs	PM	26% (312/1200)	3%	1%	18%	3%	2%
	AP	5% (36/711)	0%	0%	1%	1%	3%
	GS	31% (221/720)	1%	1%	25%	3%	1%
	MM	5% (37/720)	0%	1%	3%	1%	1%
Total SBs	ML	22% (316/1440)	5%	1%	9%	6%	1%
	FB	42% (301/720)	2%	6%	26%	7%	1%
	DDV	20% (117/600)	0%	0%	7%	9%	3%
	IC	36% (259/720)	0%	1%	22%	13%	0%

Table II. CUD (ms) and standard deviations (ms; smaller characters) broken down as a function of feature type (luminance, color, motion) and presentation type (inter-, intra-hemispheric) for each split-brain individual and means for the normal individuals group. Of note, the reported CUD for D.D.V. is solely estimated on the basis of stimuli presented in the right visual field. The group averaged CUD for total split-brain individuals do not include data from D.D.V.

		LUMINANCE				COLOUR				MOTION			
Groups		Inter		Intra		Inter		Intra		Inter		Intra	
Mean Normals		0.1	17.8	0.4	18.1	0.8	16.5	-0.3	17.9	0.8	18.6	0.5	18.2
	PM	-3.5	62.8	-4.7	72.3	-0.4	61.7	6.6	63.9	0.3	63.5	-6.5	59.7
	AP	0.8	26.3	4.3	24.3	2.7	26.2	-2.5	26.9	4.0	22.2	3.0	16.8
	GS	8.9	79.2	3.4	62.7	14.0	54.1	4.8	42.5	14.3	64.8	-8.6	55.4
Partial SBs	MM	5.7	48.1	7.5	53.5	6.7	35.0	8.4	38.9	3.8	41.5	19.1	49.6
Mean Partial SBs		3.0	54.1	2.6	53.2	7.8	44.3	4.3	43.1	5.6	48.0	1.8	45.4
	ML	41.6	62.4	17.7	44.8	41.1	55.6	18.3	40.3	31.4	65.3	40.0	43.8
	FB	22.4	73.2	32.3	63.0	30.1	62.6	20.8	76.5	-4.7	114.7	12.7	62.1
	DDV	134.3	56.5	46.6	51.6	144.4	56.7	54.8	40.5	72.6	50.9	62.7	37.3
Total SBs	IC	-1.8	83.3	9.5	70.4	22.7	69.4	32.8	130.8	0.0	97.5	0.3	57.0
Mean Total SBs		20.7	73.0	19.8	59.4	31.3	62.5	24.0	82.5	8.9	92.5	17.7	54.3

Table III. Reaction times (ms) and standard deviations (ms; smaller characters) broken down as a function of feature type (luminance, color, or motion), presentation type (inter- or intra-hemispheric), visual field (left or right), and hand (left or right) for each split-brain individual and means for the normal group.

		Interhemispheric							
		LVF		RVF		LVF		RVF	
Groups		Lh	Rh	Lh	Rh	Lh	Rh	Lh	Rh
LUMINANCE									
Normals		331.4 63.2	330.4 62.5	327.2 56.3	325.9 56.4	331.0 55.4	327.9 55.8	335.7 66.2	331.9 65.1
Partial SBs	PM	457.9 90.3	402.4 72.9	424.6 59.9	376.0 68.4	462.8 104.5	398.6 93.5	430.6 88.0	375.8 89.8
	AP	379.6 65.7	360.3 61.7	375.4 50.1	354.6 51.2	366.3 61.8	358.0 58.2	353.9 63.5	336.9 58.7
	GS	576.5 129.7	524.8 131.0	585.5 138.6	516.1 135.9	535.2 121.9	507.8 140.0	575.6 153.9	541.4 154.2
	MM	427.7 55.7	392.6 57.5	443.4 59.8	396.9 59.2	442.8 63.0	406.6 57.3	459.9 68.7	408.6 66.8
Total SBs	ML	549.7 134.1	615.0 150.6	500.3 100.3	482.5 112.2	496.3 101.4	528.5 98.2	487.4 99.7	484.2 112.0
	FB	510.5 108.2	488.5 104.6	490.2 108.3	423.5 105.0	489.2 85.5	498.4 74.1	470.1 103.9	414.7 109.6
	DDV	nil	nil	549.9 79.4	415.6 66.8	nil	nil	397.9 72.5	351.3 54.4
	IC	622.4 132.4	631.8 160.6	614.7 136.2	627.6 128.5	674.0 111.4	701.1 114.6	647.6 132.3	655.8 116.5
COLOUR									
Normals		319.0 56.7	319.8 56.5	328.2 60.8	327.5 61.0	335.8 63.8	336.7 64.5	327.7 63.8	329.2 63.9
Partial SBs	PM	432.1 88.0	376.8 79.7	426.5 84.1	371.9 81.0	461.2 92.5	415.0 85.4	450.4 98.0	391.1 83.3
	AP	388.6 51.0	369.4 47.3	398.8 68.7	374.2 65.4	393.1 56.5	368.7 52.2	395.3 60.2	375.8 59.2
	GS	539.9 154.9	529.9 168.1	565.4 163.8	527.4 169.2	481.3 63.6	460.8 68.0	504.0 100.3	473.8 102.2
	MM	505.3 68.6	495.6 61.8	489.8 61.2	466.7 49.3	479.3 58.0	471.1 55.3	504.1 80.2	479.2 72.0
Total SBs	ML	527.8 141.6	556.8 136.3	512.0 110.8	458.8 102.6	453.8 92.6	472.1 95.9	448.7 91.2	430.5 94.7
	FB	475.1 77.2	514.6 102.5	497.6 88.5	476.9 91.8	494.7 92.1	464.5 86.5	532.4 102.4	460.6 88.6
	DDV	nil	nil	523.1 52.5	378.7 57.8	nil	nil	405.8 49.2	351.0 38.6
	IC	625.9 127.7	675.3 113.0	653.9 130.5	657.9 111.4	572.7 102.9	679.6 126.5	633.1 149.3	674.4 157.2
MOTION									
Normals		369.4 64.3	369.6 65.6	367.1 66.9	365.6 66.4	366.1 71.7	364.7 71.5	367.0 67.1	364.5 67.6
Partial SBs	PM	475.4 140.4	433.3 155.5	474.2 120.3	431.6 133.0	403.1 57.5	355.5 67.0	425.5 93.8	390.8 105.2
	AP	432.0 73.1	429.7 63.3	408.6 55.1	398.2 52.7	421.7 67.6	425.4 67.4	410.8 60.2	408.5 62.2
	GS	566.7 94.5	529.5 101.2	603.1 135.4	537.2 137.4	578.8 75.5	532.4 73.9	563.9 112.7	534.6 131.8
	MM	528.0 109.4	507.8 97.2	469.6 62.9	441.9 67.7	479.9 70.5	465.2 70.0	465.0 87.0	412.2 96.3
Total SBs	ML	524.4 136.8	568.9 138.7	557.0 141.6	538.8 156.2	456.6 75.5	506.3 72.3	574.7 129.8	544.5 135.8
	FB	490.9 218.2	519.1 243.6	530.8 208.2	568.4 208.0	493.6 158.3	509.2 164.0	449.4 238.0	439.7 241.4
	DDV	nil	nil	516.5 79.3	443.9 61.9	nil	nil	477.0 75.6	414.3 66.5
	IC	674.4 136.1	732.9 120.9	702.6 133.0	761.2 122.7	654.7 126.4	668.5 104.1	679.5 132.4	692.8 130.2

Table IV. Asynchrony values (ms) and standard deviations (ms; smaller characters) broken down as a function of feature type (luminance, color, or motion), presentation type (inter- or intra-hemispheric), and number of stimuli (one or two) for each split-brain individual and means for the normal individuals group. Of note, the reported values for single stimuli for D.D.V. are solely estimated on the basis of stimuli presented on the midline or in the right visual field. The group averaged asynchrony values for total split-brain individuals do not include data from D.D.V.

		Interhemispheric				Intrahemispheric				Midline			
Groups		One		Two		One		Two		One		Two	
LUMINANCE													
Mean Normals		13.7	11.3	12.9	9.9	14.4	11.2	14.1	11.5	14.7	13.4	14.5	10.9
	PM	53.1	33.2	51.3	24.1	62.4	36.6	62.5	33.1	46.7	19.9	45.1	29.4
	AP	23.1	12.4	22.9	11.0	21.9	11.4	20.4	12.5	15.7	7.2	14.5	9.8
	GS	67.0	43.2	59.4	29.6	47.9	40.1	52.1	30.4	67.6	49.1	46.8	32.0
Partial SBs	MM	42.3	23.3	33.1	20.0	45.7	28.5	41.8	20.1	43.6	25.5	43.9	25.4
Mean Partial SBs		46.4	28.0	41.7	21.2	44.5	29.2	44.2	24.0	43.4	25.4	37.6	24.2
	ML	55.1	50.9	31.9	25.7	38.9	28.8	30.4	21.5	30.5	25.1	30.1	21.8
	FB	64.5	40.9	53.0	37.7	52.2	47.7	68.0	64.4	59.4	42.9	42.3	29.9
	DDV	134.3	56.5	36.0	24.0	53.4	44.6	45.0	32.2	33.5	24.8	29.3	20.2
Total SBs	IC	59.6	58.4	67.0	85.7	59.1	38.8	65.7	60.6	70.5	53.4	65.6	36.5
Mean Total SBs		59.7	50.1	50.6	49.7	50.1	38.4	54.7	48.8	53.5	40.5	46.0	29.4
COLOUR													
Mean Normals		12.8	10.5	12.4	9.8	13.6	11.6	13.5	11.1	13.5	13.2	12.8	10.2
	PM	55.3	27.2	52.1	26.9	56.2	31.0	56.4	35.0	42.5	23.6	38.5	20.6
	AP	24.0	10.7	20.6	8.8	24.0	12.4	22.5	10.7	25.4	13.0	26.0	8.8
	GS	44.5	33.5	37.5	20.2	35.8	23.7	47.8	77.9	44.4	33.7	41.1	23.4
Partial SBs	MM	28.9	20.6	23.0	14.6	31.2	24.5	23.0	13.4	25.0	15.3	29.7	26.7
Mean Partial SBs		38.2	23.0	33.3	17.6	36.8	22.9	37.4	34.3	34.3	21.4	33.8	19.9
	ML	50.7	47.2	29.1	22.4	36.5	24.9	37.7	32.9	27.5	18.2	23.9	15.4
	FB	52.8	44.7	26.6	22.5	60.0	51.4	54.8	46.6	39.9	36.3	42.3	32.1
	DDV	144.4	56.7	28.1	22.5	59.0	33.7	52.1	31.9	35.8	25.3	31.2	24.6
Total SBs	IC	60.0	41.1	57.0	43.2	100.7	89.7	93.3	63.6	81.2	67.5	67.3	66.4
Mean Total SBs		54.5	44.3	37.6	29.4	65.7	55.3	61.9	47.7	49.5	40.7	44.5	38.0
MOTION													
Mean Normals		14.1	12.1	13.8	11.6	14.2	11.6	13.5	10.2	13.0	9.6	13.1	9.8
	PM	53.7	33.7	50.7	31.4	49.1	31.0	44.9	23.0	63.6	39.1	50.5	20.2
	AP	17.9	13.7	16.6	7.4	15.6	6.7	16.9	7.3	16.5	6.2	17.6	7.1
	GS	57.0	33.4	42.0	24.5	47.9	28.8	59.5	76.3	61.8	52.7	44.4	38.8
Partial SBs	MM	32.5	25.9	43.0	36.3	43.9	30.9	37.4	21.2	41.6	27.9	40.9	23.3
Mean Partial SBs		40.3	26.7	38.1	24.9	39.1	24.4	39.6	32.0	45.9	31.5	38.4	22.4
	ML	54.6	48.1	26.6	20.7	48.6	45.6	57.1	41.9	28.7	30.1	22.0	19.9
	FB	72.0	88.4	77.5	38.3	51.1	38.3	49.3	44.3	45.0	54.2	40.2	33.3
	DDV	73.3	50.0	63.5	54.7	65.3	32.6	65.4	28.3	74.1	41.0	82.7	36.0
Total SBs	IC	76.9	58.9	67.3	57.2	44.8	35.0	68.0	62.2	95.9	95.9	90.7	76.7
Mean Total SBs		67.8	65.1	57.1	36.2	48.1	39.6	58.1	49.5	56.5	60.1	50.9	43.3

Table V. Mean standard deviations of asynchrony values calculated with the sign (ms) broken down as a function of feature type (luminance, color, or motion), presentation type (inter- or intra-hemispheric), and number of stimuli (one or two) for each split-brain individual and means for the normal individuals group. Mean standard deviations were computed by averaging log-transformed individual-participant variances and then reversing this transformation and taking the square root of the result to return to the original millisecond units. Of note, the reported values for single stimuli for D.D.V. are solely estimated on the basis of stimuli presented on the midline or in the right visual field. The group averaged values for total split-brain individuals do not include data from D.D.V.

		Inter		Intra		Midline	
Groups		One	Two	One	Two	One	Two
Luminance							
Mean normals		14.8	14.4	15.4	14.5	14.8	16.1
	PM	24.0	21.6	24.7	29.4	22.8	23.7
	AP	17.0	15.7	21.2	18.9	17.3	13.7
	GS	33.1	32.0	33.8	33.1	40.4	39.3
Partial SBs	MM	25.8	23.4	31.5	22.2	21.2	28.4
Mean Partial SBs		25.0	23.2	27.8	25.9	25.4	26.3
	ML	59.6	35.1	42.6	35.0	37.3	37.4
	FB	62.3	50.2	58.2	90.2	37.5	44.2
	DDV	48.7	41.4	43.2	39.7	34.6	27.7
Total SBs	IC	67.4	62.4	68.8	89.9	47.9	37.3
Mean Total SBs		63.1	49.2	56.6	71.7	40.9	39.6
Colour							
Mean normals		14.5	13.4	14.6	14.5	14.7	14.1
	PM	23.8	26.2	27.6	22.0	21.8	20.9
	AP	14.4	12.7	15.6	15.7	15.6	8.8
	GS	50.5	26.2	34.5	31.5	33.1	31.1
Partial SBs	MM	31.6	25.3	34.5	26.0	26.3	32.2
Mean Partial SBs		30.1	22.6	28.0	23.8	24.2	23.3
	ML	55.8	32.4	44.3	44.0	32.4	28.6
	FB	68.8	28.3	47.4	53.7	45.0	23.8
	DDV	56.7	29.4	40.5	39.0	33.8	35.2
Total SBs	IC	68.0	71.7	93.2	74.5	63.2	47.8
Mean Total SBs		64.2	44.2	61.6	57.4	46.9	33.4
Motion							
Mean normals		14.9	14.8	14.9	14.8	13.7	14.1
	PM	33.4	27.9	26.3	25.3	28.5	17.2
	AP	16.1	17.5	17.0	18.0	16.7	18.8
	GS	41.7	33.0	36.6	37.7	42.0	37.0
Partial SBs	MM	34.0	41.4	40.9	30.3	33.8	37.7
Mean Partial SBs		31.3	29.9	30.2	27.8	30.2	27.7
	ML	59.5	28.2	50.4	64.8	30.1	24.5
	FB	86.6	78.9	56.8	66.6	36.1	47.4
	DDV	41.4	41.8	37.3	28.3	37.9	36.0
Total SBs	IC	77.8	68.6	55.3	80.3	71.9	75.0
Mean Total SBs		74.6	58.6	54.2	70.6	46.0	48.9

Table VI. A: Total number and percentage of omissions and hits for each hand for stimuli presented in the left visual field of D.D.V. in the interhemispheric condition. B: Mean RTs for the left and right hand to stimuli presented in the left visual field as a function of the number of responding hands. Included in parentheses are the numbers of trials contributing to mean RT.

A	LVF of DDV	
	Lh	Rh
Omissions (%)	143 (79%)	163 (91%)
Hits (%)	37 (21%)	17 (9%)

B	Lh	Rh
	RTs (trials)	RTs (trials)
One-hand resp.	387.5 (24)	688.3 (4)
Two-hand resp.	454.3 (13)	493.3 (13)

FIGURE CAPTIONS

Figure 1. A: The four possible stimulus positions used for the CUD (filled circles) and the six possible stimulus positions used for the asynchrony measure (filled and empty circles). For the CUD, only one stimulus appears per trial. B: Representation of single and redundant trials occurring as a function of different presentation types (inter, intra, or midline). Single stimuli in the intrahemispheric blocks consistently appeared in the same vertical hemifield (right or left side of fixation) but randomly appeared in the upper or lower hemifield. Single stimuli in the interhemispheric blocks consistently appeared in the same horizontal hemifield (upper or lower) but randomly appeared to the left or right of fixation. Single stimuli in the midline blocks consistently appeared on the vertical meridian but randomly appeared in the upper or lower hemifield. Redundant trials entailed a simultaneous presentation of two stimuli either in the interhemispheric, intrahemispheric, or midline condition. Note that redundant interhemispheric and midline presentations simultaneously activated two hemispheres whereas an intrahemispheric presentation only initially activated a single hemisphere.

Figure 2. A: CUD for each group. B: CUD for luminance, colour, or motion stimuli for each group. Error bars show the standard error of the mean.

Figure 3. A: Asynchrony values for interhemispheric, intrahemispheric, or midline stimuli presented singly or redundantly for each group. B: Asynchrony values for

luminance, colour, or motion stimuli presented singly or redundantly for each group. Error bars show the standard error of the mean.

Figure 4. A: Mean standard deviations of asynchrony for interhemispheric, intrahemispheric, or midline stimuli presented singly or redundantly for each group. B: Mean standard deviations of asynchrony for luminance, colour, or motion stimuli presented singly or redundantly. Error bars show the standard error of the mean.

Figure 1

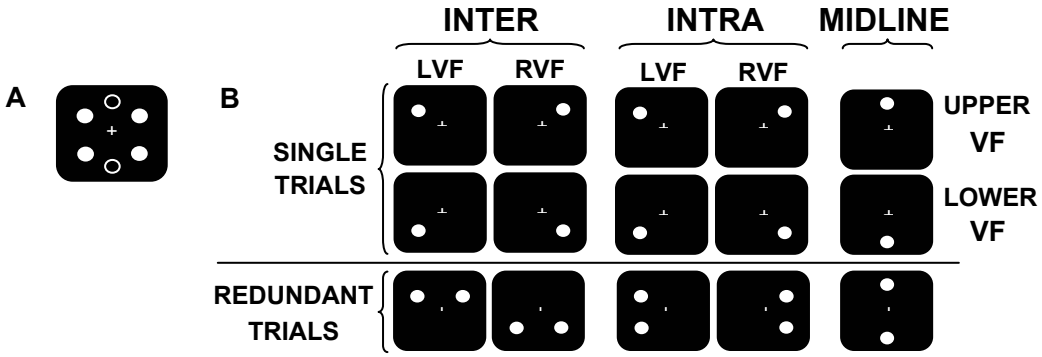

A
B
INTER
INTRA
MIDLINE
LVF
RVF
LVF
RVF
SINGLE TRIALS
REDUNDANT TRIALS
UPPER VF
LOWER VF

Figure 2

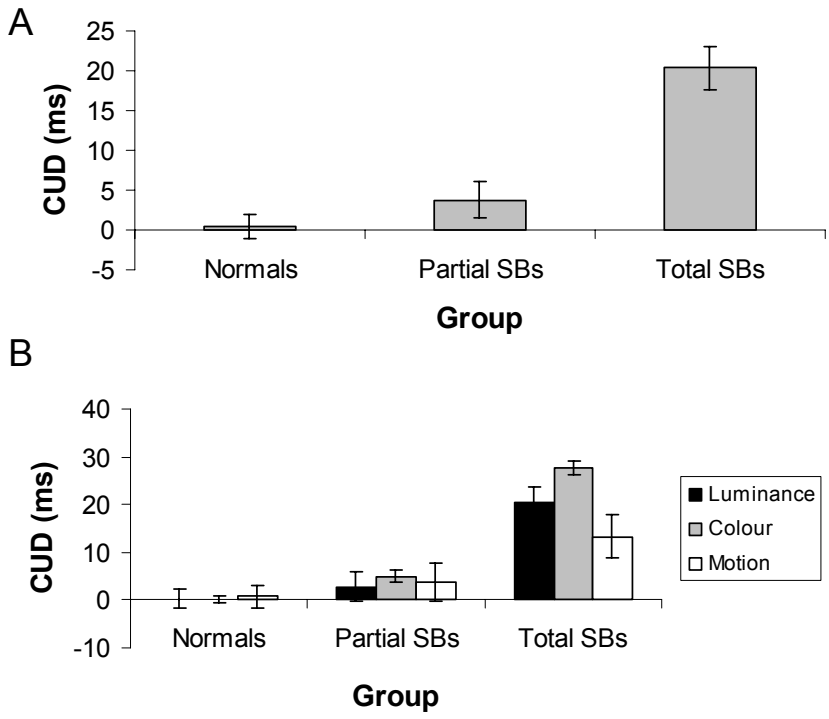

A
25
20
15
10
5
0
-5
CUD (ms)
Normals
Partial SBs
Total SBs
Group
B
40
30
20
10
0
-10
CUD (ms)
Normals
Partial SBs
Total SBs
Group
Luminance
Colour
Motion

Figure 3

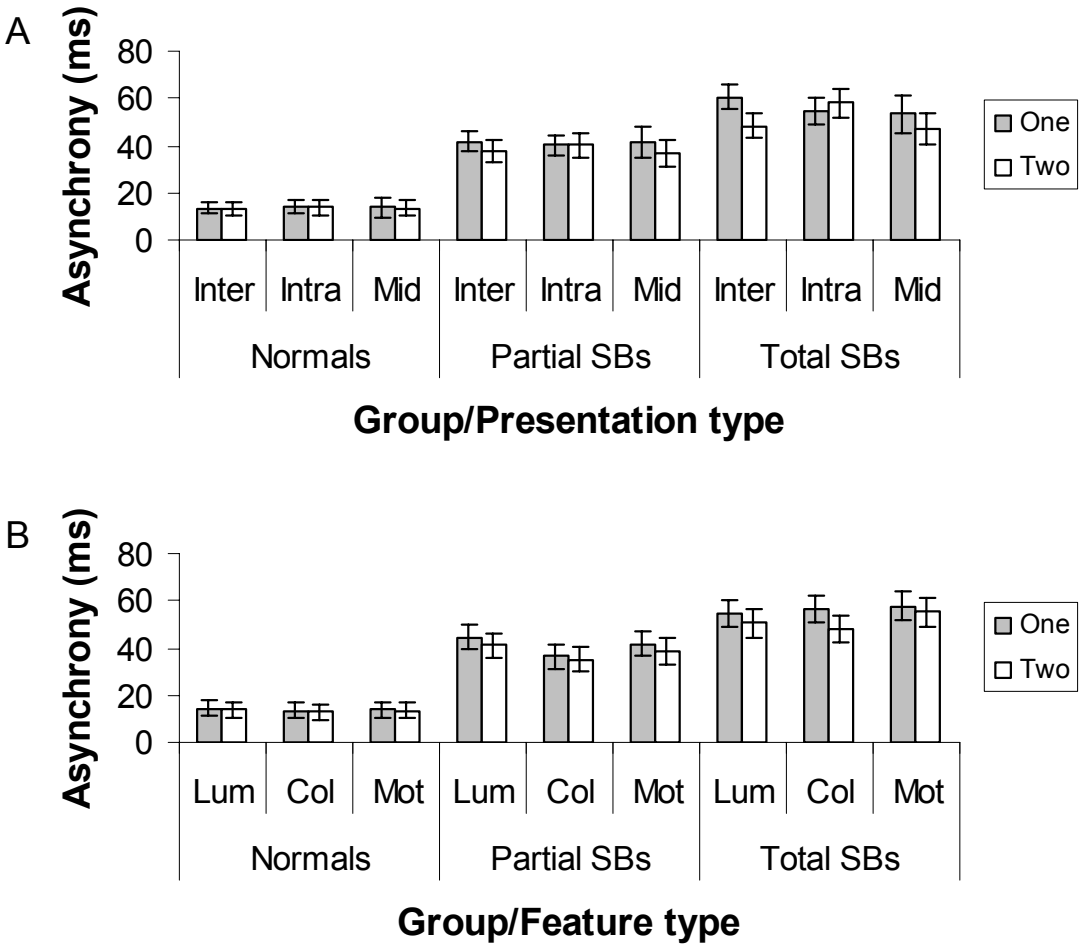
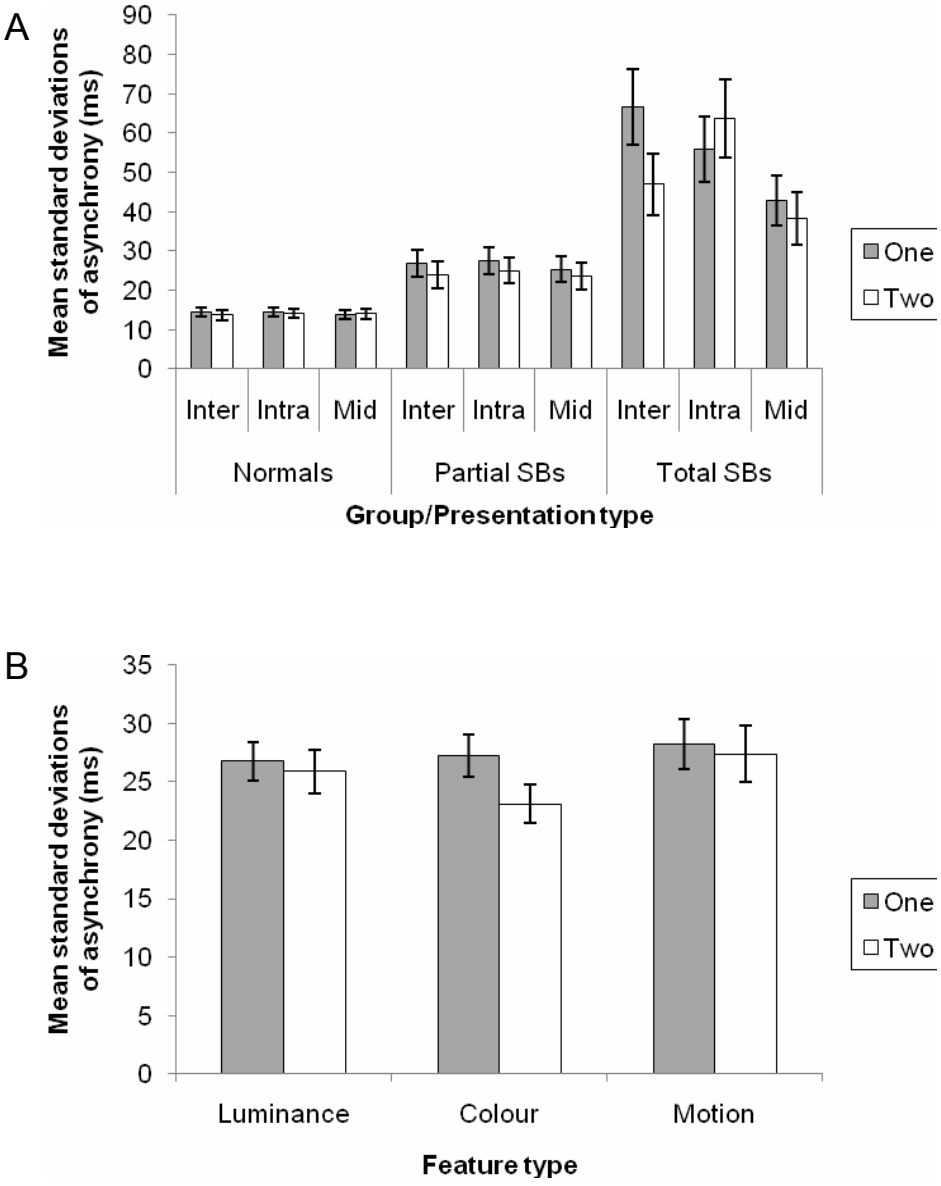

A
Asynchrony (ms)
80
60
40
20
0
One
Two
Inter
Intra
Mid
Normals
Partial SBs
Total SBs
Group/Presentation type
B
Asynchrony (ms)
80
60
40
20
0
One
Two
Lum
Col
Mot
Normals
Partial SBs
Total SBs
Group/Feature type

Figure 4


A
Mean standard deviations of asynchrony (ms)
90
80
70
60
50
40
30
20
10
0
Inter
Intra
Mid
Inter
Intra
Mid
Inter
Intra
Mid
Normals
Partial SBs
Total SBs
Group/Presentation type
One
Two
B
Mean standard deviations of asynchrony (ms)
35
30
25
20
15
10
5
0
Luminance
Colour
Motion
Feature type
One
Two

APPENDIX 1

An ANOVA was performed on the RTs using group (normal, partial, and total) as a between-subjects factor and feature type (luminance, colour, motion), presentation type (interhemispheric, intrahemispheric), visual field (left, right), and hand (left, right) as within-subjects factors. Means are shown in Table III. Main effects of group, feature type, presentation type, and hand were found significant, all $p <$. 025. The main effect of group was driven by the RTs of normal individuals (341.6 ms) being shorter than those of partial (450.6 ms) and total (554.1 ms) split-brain individuals, both $p < .019$. In turn, RTs of split-brain groups did not significantly differ, $p > .10$. The main effect of feature type revealed that RTs to motion stimuli (470.1 ms) were slower than RTs to luminance (437.4 ms) and colour stimuli (438.8 ms), both $p < .002$. The main effect of presentation type revealed that RTs in the interhemispheric condition (454.1 ms) were longer than RTs in the intrahemispheric condition (443.4 ms), $p < .007$. Also, RTs recorded from the right hand (444.8 ms) were shorter than RTs recorded from the left hand (452.8 ms), $p < .025$. Finally, no main effect of visual field was found, $F(1, 14) = 2.0$, $MSE = 874.3$, $p > .17$.

Significant two-way interactions were also identified. As expected, the factors hand and visual field interacted, $F(1, 14) = 41.2$, $MSE = 129.2$, $p < .001$, showing that right-hand RTs (438.3 ms) were on average shorter than left-hand RTs (454.5 ms) when stimuli were presented in the right visual field, $p < .001$, whereas no hand difference was found when stimuli were presented in the left visual field (Lh: 451.0

ms, Rh: 451.2 ms), $p > .95$. Hand and group interacted, $F(2, 14) = 14.5$, $MSE = 805.1$, $p < .001$, indicating that partial split-brain individuals exhibited shorter right-hand mean RTs (434.1 ms) as compared to left-hand mean RTs (467.1 ms), $p < .001$, whereas other groups did not show a significant difference between the hands (Total SBs- Rh: 559.0 ms, Lh: 549.1 ms; Normals- Rh: 342.1 ms, Lh: 341.1 ms), both $p > .16$. Hand also interacted with feature type, $F(2, 28) = 4.3$, $MSE = 198.9$, $p < .024$, with faster right-hand responses (430.4 ms) as compared to left-hand responses (444.5 ms) when luminance stimuli were presented, $p < .003$, whereas no such difference was found for colour (Lh: 442.3 ms, Rh: 435.3 ms) or motion (Lh: 471.6 ms, Rh: 468.6 ms) stimuli, both $p > .15$. Also, feature type and presentation type interacted, $F(2, 28) = 3.7$, $MSE = 1160.2$, $p < .049$, suggesting that an intrahemispheric presentation (458.6 ms) yielded faster responses than an interhemispheric presentation (481.5 ms) when stimuli were defined by motion but not when stimuli were defined by luminance (inter: 437.4 ms, intra: 437.4 ms) or colour (inter: 443.3 ms, intra: 434.3 ms), both $p > .19$. Finally, presentation type interacted with group, $F(2, 14) = 6.0$, $MSE = 914.4$, $p < .013$, indicating that RTs to interhemispheric stimuli (565.5 ms) were longer than RTs to intrahemispheric targets (542.6 ms) for total split-brain individuals, $p < .006$, whereas no such difference was found for partial split-brain (inter: 456.7 ms, intra: 444.5 ms), $p > .07$, and normal individuals (inter: 340.1 ms, intra: 343.2 ms). This finding has been previously discussed elsewhere (Ouimet et al., 2009).

Three-way interactions were also identified. Feature type, hand and visual field interacted, $F(2, 28) = 4.2$, $MSE = 45.3$, $p < .029$. Across all feature types, the right hand (luminance: 419.0, colour: 429.1, motion: 466.8 ms) was significantly faster than the left hand (luminance: 440.9, colour: 447.0, motion: 475.7 ms) when responding to stimuli presented in the right visual field, all $p < .05$, whereas right hand (luminance: 441.7 ms, colour: 441.6 ms, motion: 470.4 ms) and left hand (luminance: 448.1 ms, colour: 437.5 ms, motion: 467.5 ms) yielded statistically equivalent RTs when stimuli were presented in the left visual field, all $p > .13$. Feature type, visual field, and group also interacted, $F(4, 28) = 3.0$, $MSE = 924.2$, $p < .034$, illustrating a right visual field advantage (524.9 ms) for total split-brain individuals as compared to left (567.1 ms) when stimuli were defined by luminance, $p < .001$, but not by colour (RVF: 536.4 ms, LVF: 542.7 ms), $p > .68$, or motion (RVF: 586.6 ms, LVF: 566.6 ms), $p > .09$. No such difference was found for partial split-brain (Lum- RVF: 434.7 ms, LVF: 437.5 ms; Col- RVF: 449.7 ms, LVF: 448.0 ms; Mot- RVF: 461.0 ms, LVF: 472.8 ms) and normal (Lum- RVF: 330.2 ms, LVF: 330.1 ms; Col- RVF: 328.2 ms, LVF: 327.8 ms; Mot- RVF: 366.0 ms, LVF: 367.5 ms) individuals, all $p > .23$. Importantly, an interaction involving visual field, hand, and group was found, $F(2, 14) = 21.5$, $MSE = 129.2$, $p < .001$. Total split-brain individuals showed faster left-hand (543.7 ms) than right-hand (574.0 ms) responses when stimuli were presented in the left visual field, $p < .001$, and showed faster right-hand (544.0 ms) than left-hand (554.6 ms) responses when stimuli were presented in the right visual field, although not significantly so, $p > .19$. Partial split-brain individuals showed faster right-hand (LVF: 438.2 ms, RVF: 430.1 ms) than

left-hand (LVF: 467.3 ms, RVF: 466.8 ms) responses for both visual fields, $p < .001$, whereas RTs of normal individuals did not significantly vary for the right (LVF: 341.5 ms, RVF: 340.8 ms) and left (LVF: 342.1 ms, RVF: 342.1 ms) hand as a function of visual field, all $p > .74$.

Finally, feature type, visual field, hand, and group interacted into a four-way interaction, $F(4, 28) = 3.1$, $MSE = 45.3$, $p < .034$. In fact, feature type interacted with the three-way interaction previously described. When stimuli were defined by luminance and colour, total split-brain individuals showed faster responses with the right hand (lum: 514.7 ms, col: 526.5 ms) as compared to the left hand (lum: 535.1 ms, col: 546.3 ms) when stimuli were presented in the right visual field, all $p < .047$ (except for a trend in the case of colour stimuli presented in the right visual field, $p > .056$), and faster responses with the left hand (lum: 557.0 ms, col: 525.0 ms) as compared to the right hand (lum: 577.2 ms, col: 560.5 ms) when stimuli were presented in the left visual field, all $p < .029$. Conversely, when stimuli were defined by motion, total split-brain individuals showed faster responses with the left hand (549.1 ms) as compared to the right hand (584.2 ms) when stimuli were presented in the left visual field, $p < .001$, but the response speed of the two hands (Lh: 582.3 ms, Rh: 590.9 ms) did not significantly differ when stimuli were presented in the right visual field, $p > .34$. Partial split-brain individuals showed systematically faster right-hand responses (Lum- RVF: 413.3 ms, LVF: 418.9 ms; Col- RVF: 432.5 ms, LVF: 435.9 ms; Mot- RVF: 444.4 ms, LVF: 459.5 ms) as compared to left-hand responses (Lum- RVF: 456.1 ms, LVF: 456.1 ms; Col- RVF: 466.8 ms, LVF: 460.1

ms; Mot- RVF: 477.6 ms, LVF: 485.7 ms) irrespective of visual field and feature type, all $p < .013$. In turn, normal individuals' right hand (Lum- RVF: 328.9 ms, LVF: 329.1 ms; Col- RVF: 328.4 ms, LVF: 328.3 ms; Mot- RVF: 365.0 ms, LVF: 367.1 ms) and left hand (Lum- RVF: 331.4 ms, LVF: 331.2 ms; Col- RVF: 328.0 ms, LVF: 327.4 ms; Mot- RVF: 367.0 ms, LVF: 367.8 ms) RTs did not significantly vary as a function of feature type and visual field, all $p > .62$.

DISCUSSION GÉNÉRALE

RAPPEL DES OBJECTIFS EXPÉRIMENTAUX ET DES PRINCIPAUX RÉSULTATS

La présente thèse a permis d'approfondir nos connaissances sur l'implication du corps calleux dans le transfert interhémisphérique de l'information. D'abord, un portrait des principaux signes de déconnexion calleuse a été dressé pour l'ensemble des fonctions sensorielles et cognitives. Puis, dans une première étude empirique, à l'aide d'un paradigme de GR, il a été montré que les hémisphères cérébraux d'individus callosotomisés peuvent travailler de concert malgré l'absence du corps calleux. Dans une seconde étude empirique, à l'aide d'un paradigme de DCNC et d'une mesure d'asynchronie bimanuelle, il a été montré que des difficultés de communication peuvent aussi émerger en l'absence, même partielle, du corps calleux. L'analyse conjuguée de ces trois mesures a permis d'émettre des propositions quant aux processus sous-tendant différents types de transfert interhémisphérique. Des conclusions ont aussi été dégagées grâce aux effets sur chaque mesure des manipulations sensorielles et attentionnelles. Malgré tout, des limites à nos conclusions ont été identifiées et des avenues futures de recherche ont été proposées.

PROCESSUS SOUS-TENDANT LE GR, LA DCNC ET LA COORDINATION BIMANUELLE

Nos résultats ont indiqué que le GR des individus ayant subi une section partielle ou totale du corps calleux est significativement plus grand que celui des individus

normaux. La mesure d'asynchronie bimanuelle a montré ce même patron de résultats entre les groupes, c'est-à-dire que les deux groupes d'individus callosotomisés se sont révélés plus asynchrones que les individus normaux. Une section antérieure du corps calleux est donc suffisante pour perturber le traitement normal de l'information donnant lieu au GR et à la synchronisation des mains. Ceci suggère la possibilité qu'un processus commun, probablement relié aux cortex moteurs, sous-tende le transfert interhémisphérique à l'origine de ces deux mesures. Aussi, la présente thèse a abordé des questions relatives au transfert d'informations donnant lieu à la DCNC. Les individus totalement callosotomisés ont montré une DCNC beaucoup plus grande que celle des individus normaux alors que les individus antérieurement callosotomisés ont montré une DCNC similaire à celle des individus normaux. À l'inverse du GR et de la synchronie bimanuelle, il semblerait donc qu'une section antérieure du corps calleux ne suffise pas à perturber significativement l'échange interhémisphérique d'informations donnant lieu à la DCNC. Sur la base de ces résultats, il est suggéré que les processus sous-tendant la DCNC diffèrent de ceux sous-tendant le GR et l'asynchronie bimanuelle. Cette conclusion appuie la proposition selon laquelle des processus différents sont à l'origine du GR et de la DCNC (Corballis, 2002). Or, au meilleur de nos connaissances, la proposition qu'un processus commun sous-tende le GR et la synchronie bimanuelle n'avait jusqu'alors pas été formulée, ni celle d'une dissociation entre les processus sous-tendant la DCNC et l'asynchronie bimanuelle.

Nos résultats permettent aussi d'émettre des conclusions générales sur la disposition anatomique des fibres calleuses dédiées au transfert d'informations sous-tendant le GR, la DCNC et la synchronisation des mains. À la lumière des données recueillies, il semblerait que de l'information contribuant à la synchronie bimanuelle et au GR transfère dans la portion antérieure du corps calleux. Cette proposition est congruente avec des données d'imagerie selon lesquelles, dans une tâche de coordination bimanuelle, les performances varient en fonction de l'intégrité d'une région spécifique du tronc du corps calleux (Johansen-Berg, Della-Maggiore, Behrens, Smith, & Paus, 2007). Spécifiquement, cette région relierait les aires motrices supplémentaires des deux hémisphères. Les présentes données fournissent donc un argument comportemental selon lequel une section antérieure du corps calleux suffit à provoquer une désynchronisation des réponses manuelles.

Aussi, étant donné que les individus ayant subi une section antérieure du corps calleux ont montré une DCNC semblable à celle des individus normaux, alors que l'inverse s'est produit pour la synchronie bimanuelle, il est possible d'inférer que l'information donnant lieu à la DCNC transfère dans une portion plus postérieure du corps calleux que celle contribuant à la synchronie bimanuelle. Encore une fois, cette proposition est congruente avec des données d'imagerie fonctionnelle recueillies dans le contexte d'une tâche de DCNC exécutée par des individus normaux. Une comparaison d'activation entre les essais croisés et non-croisés a révélé une activation accrue lors des essais croisés dans les régions préfrontales bilatérales, prémotrices dorsales bilatérales, ainsi que dans l'aire pariétale supérieure

droite, supportant ainsi l'idée d'un transfert parallèle d'informations s'opérant à plusieurs niveaux (Iacoboni & Zaidel, 2004). L'implication du genou du corps calleux dans le transfert interhémisphérique lié à la DCNC a aussi été évoquée chez les individus normaux (Omura et al., 2004). Les résultats de la présente thèse supportent la position selon laquelle le transfert de l'information donnant lieu à la DCNC s'opère en parallèle et de manière étendue dans le corps calleux, suggérant une implication simultanée de plusieurs régions calleuses. La DCNC serait donc produite en fonction de la vitesse de transfert des différentes fibres calleuses. Davantage d'études doivent toutefois être menées de manière à confirmer et spécifier l'implication respective des différentes régions calleuses dans le transfert interhémisphérique.

MANIPULATIONS SENSORIELLES DU GR ET DE LA DCNC

À l'inverse du GR des individus normaux, celui des deux groupes d'individus callosotomisés a montré une tendance à varier en fonction des caractéristiques définissant les stimuli. Ce résultat semble s'opérer en fonction des différences d'efficacité dans le transfert interhémisphérique respectivement associées aux traitements de nature corticale ou sous-corticale. Spécifiquement, nos données suggèrent la présence d'un supra-GR lorsque l'échange interhémisphérique s'opère à un niveau sous-cortical, résultat qui appuie les conclusions d'études antérieures (Savazzi & Marzi, 2004). Aussi, puisque le GR de ces groupes s'est montré sensible aux manipulations sensorielles, une contribution sensorielle au supra-GR des

individus callosotomisés est aussi postulée. Toutefois, un support empirique plus substantiel est souhaitable pour appuyer cette conclusion et pour poursuivre la recherche du locus du supra-GR chez les individus callosotomisés.

Pour la DCNC, seuls les individus ayant subi une section complète du corps calleux ont montré un effet de la manipulation des paramètres visuels. Ce résultat s'inscrit en continuité avec des études montrant que la DCNC des individus callosotomisés varie en fonction de différentes manipulations visuelles (Clarke & Zaidel, 1989). Toutefois, bien que la modulation de la DCNC en fonction de la manipulation de certains paramètres visuels soit maintenant établie, il demeure qu'une spécification du type de manipulations visuelles l'affectant doit être poursuivie. À cet effet, Clarke et Zaidel (1989) ont suggéré que la DCNC, chez les individus callosotomisés, s'opère à un niveau sous-cortical qui soit sensible à la variation de l'excentricité des stimuli, mais insensible à la variation de leur luminance.

MANIPULATIONS ATTENTIONNELLES

La comparaison des présentations inter-, intra-hémisphériques et sur le méridien vertical a aussi mené à d'intéressantes conclusions. Dans un premier lieu, nous avons proposé que les individus ayant subi une section totale du corps calleux déploient leur attention différemment en comparaison aux individus normaux. Cette proposition s'appuie sur la constatation que, malgré la parfaite similarité des stimuli simples en présentation inter- et intra-hémisphérique, seuls les individus ayant subi

une section complète du corps calleux ont montré un désavantage lors des présentations interhémisphériques par rapport aux présentations intrahémisphériques. Il est spéculé que, dans de telles conditions, leurs ressources attentionnelles seraient déployées de manière à surveiller l'ensemble du champ visuel, alors que dans la présentation intrahémisphérique, leurs ressources attentionnelles seraient plutôt déployées *a priori* vers l'hémichamp visuel attendant la stimulation. Ainsi, pour les individus ayant subi une section complète du corps calleux, ceci peut conférer un avantage attentionnel lors des essais intrahémisphériques. Notre interprétation s'accorde d'ailleurs avec la position de Kinsbourne (1970) et Banich (1998) selon laquelle le corps calleux s'inscrit dans un réseau attentionel et sert spécifiquement à une redistribution dynamique des ressources attentionnelles entre les hémisphères (Banich, 2003). Alternativement, nos résultats peuvent aussi refléter un effet de préparation motrice. En effet, il est plausible qu'une stimulation répétée d'un même hémisphère contribue à faciliter la préparation motrice d'une même main, ce qui pourrait ainsi se traduire en une diminution des TR lorsque les stimuli sont présentés de manière intrahémisphérique.

Dans un deuxième temps, nos données ont permis l'évaluation d'un aspect du modèle de coactivation interhémisphérique de Miller (2004). L'hypothèse selon laquelle une stimulation bilatérale est nécessaire pour produire un supra-GR chez les ICD, mais non chez les individus normaux, a été évaluée en comparant les stimuli simples présentés sur le méridien vertical ou en périphérie. En accord avec cette prédiction, les TR aux essais simples pour les individus ayant subi une section

complète du corps calleux ont été plus rapides lorsque les stimuli étaient présentés sur le méridien vertical plutôt que de manière intra- ou interhémisphérique. Tel que prédit par le modèle de Miller (2004), un stimulus présenté sur le méridien vertical, qui active supposément les deux hémisphères, suffit donc à produire des réponses plus rapides que les stimuli en périphérie dont le traitement initial est limité à un seul hémisphère.

Dans un troisième temps, l'effet de prédictibilité spatiale sur la DCNC a été investiguée. Spécifiquement, la DCNC n'a pas varié en fonction des présentations intra- versus inter-hémisphériques, respectivement associées à une position prédictible ou non prédictible pour l'apparition des stimuli. Ce résultat s'inscrit en contradiction avec l'effet de manipulation de la prédictibilité spatiale identifiée chez un individu ayant subi une section complète du corps calleux (Aglioti et al., 1993). Or, l'identification d'une variable confondante introduite dans cette étude et la rectification de cette situation grâce à notre propre étude jettent un nouvel éclairage quant aux effets de manipulations attentionnelles sur la DCNC. Nos résultats suggèrent que les valeurs rapportées par Aglioti et al. (1993) ressemblent davantage à celles de notre patient callosotomisé présentant un phénomène d'extinction du champ visuel gauche, plutôt qu'à celles de notre groupe d'individus callosotomisés ne présentant pas de telles manifestations. Cette constatation met ainsi en doute l'interprétation des résultats rapportés par Aglioti et collaborateurs et suggère plutôt que la DCNC n'est pas sensible à la manipulation de la prédictibilité spatiale.

Finalement, tout comme le GR, la synchronie bimanuelle s'est révélée variable en fonction de la stimulation unique d'un hémisphère en comparaison à la stimulation de deux hémisphères. Nos données montrent que la stimulation simultanée des deux hémisphères a permis aux individus callosotomisés de synchroniser leurs réponses davantage que lorsqu'un seul hémisphère était stimulé. La variabilité du GR et de la synchronie bimanuelle, mais non de la DCNC, aux manipulations de nature attentionnelle, fournit un support supplémentaire à l'hypothèse selon laquelle un processus commun, différent de ceux impliqués dans la DCNC, est à l'origine du GR et de la synchronie bimanuelle.

LIMITES DES ÉTUDES

Les résultats de la présente thèse doivent être interprétés à la lumière de quelques limites associées à nos études. Certaines de ces considérations reflètent des difficultés couramment rencontrées dans l'étude de populations cliniques rares.

Limites statistiques

De nombreux résultats recueillis auprès d'individus callosotomisés s'appuient sur des études de cas, ce qui empêche la généralisation des conclusions à l'ensemble de la population callosotomisée. Dans le cadre de nos études, des efforts ont été déployés afin de créer des groupes suffisamment nombreux dans le but de permettre l'usage de statistiques traditionnelles. Il demeure néanmoins qu'un très faible

nombre de patients ont constitué chacun de nos groupes d'individus callosotomisés, limitant significativement la puissance statistique et par conséquent la fiabilité des résultats. Il demeure que les résultats obtenus sont pour la plupart congruents avec les prédictions émises sur la base d'études antérieures. Il est toutefois souhaitable que la recherche se poursuive et témoigne de la reproductibilité des patrons de résultats obtenus.

Limites relatives à l'échantillon de patients

Dans nos études, les individus callosotomisés ont été comparés à des individus normaux. L'ajout d'un groupe contrôle composé de sujets épileptiques aurait été souhaitable afin de bien dissocier les effets dus à la callosotomie *per se* des effets dus aux possibles dommages causés par l'épilepsie ou la prise de médication. De plus, ces sujets contrôles auraient idéalement été pairés aux individus callosotomisés sur la base de leur quotient intellectuel et de leur locus épileptique. En bref, il ne peut être écarté que certaines différences dans la composition des groupes aient introduit des variables confondantes pouvant fournir des explications alternatives à certaines de nos conclusions.

La composition des stimuli définis par le mouvement

Tel que discuté dans la seconde étude, un doute demeure quant à la voie visuelle par laquelle nos stimuli de couleur étaient préférentiellement traités. Ce doute émerge en

raison de la distinction entre le mouvement global, dont le traitement s'opère supposément au niveau cortical (Livingstone & Hubel, 1987), et la détection générale de mouvement qui peut aussi être traité au niveau sous-cortical (Naikar, 1996). Dans le but d'éviter l'ambiguïté qui caractérise le traitement de nos stimuli de mouvement, il aurait été préférable d'utiliser des stimuli réellement définis par du mouvement global. Dans le présent cas, des stimuli se déplaçant de manière cohérente sur un fond d'écran composé de stimuli se déplaçant aléatoirement ont d'abord été utilisés. Or, lors d'essais préliminaires, ce type de stimuli s'est révélé trop difficile à détecter pour les individus callosotomisés. Nous avons donc dû adapter les stimuli et le compromis a impliqué l'utilisation d'un fond d'écran statique. La composition de nos stimuli de mouvement soulève donc une ambiguïté et exige que davantage de recherches soient effectuées en utilisant un type de mouvement qui stimule préférentiellement, et sans équivoque, une seule voie de traitement.

AVENUES FUTURES DE RECHERCHE

Comme il en a été question dans la première étude de cette thèse, le système attentionnel des ICD semble opérer différemment de celui des individus normaux. Dans certaines tâches attentionnelles, la séparation des hémisphères cérébraux semble même contribuer à améliorer les performances. À titre d'exemple, dans une tâche de recherche visuelle, Luck, Hillyard, Mangun et Gazzaniga (1989) ont montré que la vitesse de recherche des individus callosotomisés est plus grande que celle

des individus normaux lorsque la recherche s'effectue sur l'ensemble du champ visuel. Il a été conclu que l'attention peut être déployée de manière indépendante par chacun des hémisphères cérébraux suite à une callosotomie. Poursuivre cette orientation de recherche permettrait donc d'améliorer notre connaissance du système attentionnel et de qualifier l'implication possible du corps calleux dans la distribution des ressources attentionnelles.

À l'instar des patients callosotomisés, l'étude d'autres populations peut s'avérer informative pour spécifier les fonctions du corps calleux. À titre d'exemple, il est rapporté que les hémisphères cérébraux d'adultes âgés tendent davantage à diviser le travail entre les hémisphères en comparaison aux jeunes adultes (Reuter-Lorenz & Stanczak, 2000). Il a donc été suggéré que le rôle du corps calleux s'accroît avec le passage du temps pour certains individus. Il serait dès lors pertinent de spécifier les tâches dans lesquelles cet accroissement d'implication peut être observé, et peut-être même tenter d'établir un lien avec le vieillissement normal ou pathologique.

Finalement, les déficits associés au sous-développement calleux chez les enfants sont aussi à explorer. Entre autres, le syndrome Gilles de la Tourette, la dyslexie et l'épilepsie sont des conditions neurologiques corrélées avec la taille du corps calleux (Tae, Hong, Joo, Han, Cho, Seo et al., 2006; von Plessen, Lundervold, Duta, Heiervang, Klauschen, Smievoll et al., 2002; Plessen, Wentzel-Larsen, Hugdahl, Feineigle, Klein, Staib et al., 2004). L'interprétation de telles données doit toutefois s'opérer avec prudence puisqu'il est difficile de déterminer si un dysfonctionnement

des aires corticales module la connectivité du corps calleux ou si, à l'inverse, une atrophie du corps calleux perturbe le développement cortical. L'exploration de l'ensemble de ces avenues fournirait ainsi davantage d'indices pour permettre la formulation de modèles témoignant d'une compréhension intégrée du corps calleux.

RÉFÉRENCES

Aboitiz, F. (1992). Inter-hemispheric fiber systems and anatomical asymmetries in the human brain. *Biol Res, 25*, 51-61.

Aboitiz, F., Lopez, J., & Montiel, J. (2003). Long distance communication in the human brain: timing constraints for inter-hemispherci synchrony and the origin of brain lateralization. *Biol Res, 36*, 89-99.

Achiron, R., & Achiron, A. (2001). Development of the human fetal corpus callosum: a high-resolution, cross-sectional sonographic study. *Ultrasound Obstet Gynecol, 18*(4), 343-347.

Aglioti, S., Berlucchi, G., Pallini, R., Rossi, G. F., & Tassinari, G. (1993). Hemispheric control of unilateral and bilateral responses to lateralized light stimuli after callosotomy and in callosal agenesis. *Exp Brain Res, 95*, 151-165.

Banich, M. T. (2003). Interacting hemispheres : A means of modulating attention. In E. Zaidel & M. Iacoboni (Eds.), *The Parallel Brain: The cognitive neuroscience of the corpus callosum* (pp. 267-270). Cambridge: MIT Press.

Bashore, T. R. (1981). Vocal and manual reaction time estimates of interhemispheric transmission time. *Psychol Bull, 89*, 352-368.

Bear, M. F., Connors, B. W., & Paradiso, M. A. (2007). *Neurosciences à la découverte du cerveau- 3ème édition*. Paris.

Berlucchi, G., Buchtel, H. A., & Lepore, F. (1978). Successful interocular transfer of visual pattern discriminations in split-chiasm cats with section of intertectal and posterior commissures. *Physiol Behav, 20*, 331-338.

Bogen, J. E., Fisher, E. D., & Vogel, P. J. (1965). Cerebral commissurotomy: A second case report. *J Amer Med Ass, 194*, 1328-1329.

Burton, B. K. (2007). Agenesis of the corpus callosum. In P. Kumar & B. K. Burton (Eds.), *Congenital malformations: evidence-based evaluation and management*. New York: McGraw-Hill Professional.

Chao, Y. P., Cho, K. H., Yeh, C. H., Chou, K. H., Chen, J. H., & Lin, C. P. (2009). Probabilistic topography of human corpus callosum using cytoarchitectural parcellation and high angular resolution diffusion imaging tractography. *Hum Brain Mapp, 30*(10), 3172-3187.

Chapman, C., Hoag, R., & Giaschi, D. (2004). The effect of disrupting the human magnocellular pathway on global motion perception. *Vision Research, 44*, 2551–2557.

Clarke, J. M., & Zaidel, E. (1989). Simple reaction times to lateralized light flashes. *Brain, 112*, 849-870.

Clarke, S. (2003a). Complexity of human interhemispheric connections. In E. Zaidel & M. Iacoboni (Eds.), *The Parallel Brain: The cognitive neuroscience of the corpus callosum*. Cambridge: MIT Press.

Clarke, S. (2003b). The role of homotopic and heterotopic callosal connections in humans. In E. Zaidel & M. Iacoboni (Eds.), *The parallel brain: The cognitive neuroscience of the corpus callosum*. Cambridge: MIT Press.

Cook, N. D. (1986). *The brain code: mechanisms of information transfer and the role of the corpus callosum*. New York: Methuen.

Corballis, M. C. (1998). Interhemispheric Neural Summation in the Absence of the Corpus Callosum. *Brain, 121*, 1795-1807.

Corballis, M. C., Hamm, J. P., Barnett, K. J., & Corballis, P. M. (2002). Paradoxical interhemispheric summation in the split brain. *J Cog Neurosci, 14*, 1151-1157.

Eliassen, J. C., Baynes, K., & Gazzaniga, M. S. (2000). Anterior and posterior callosal contribution to simultaneous bimanual movements of the hands and fingers. *Brain, 123*, 2501-2511.

Fandino-Franky, J., Torres, M., Narino, D., & Fandino, J. (2000). Corpus callosotomy in Columbia and some reflections on care and research among the poor in developing countries. *Epilepsia, 41* (Suppl 4), S22-27.

Forster, B., Cavina-Pratesi, C., Aglioti, S. M., & Berlucchi, G. (2002). Redundant target effect and intersensory facilitation from visual-tactile interactions in simple reaction time. *Exp Brain Res, 143*(4), 480-487.

Gielen, S. C., Schmidt, R. A., & Van den Heuvel, P. J. (1983). On the nature of intersensory facilitation of reaction time. *Percept Psychophys, 34*(2), 161-168.

Giray, M., & Ulrich, R. (1993). Motor coactivation revealed by response force in divided and focused attention. *J Exp Psychol Hum Percept Perform, 19*(6), 1278-1291.

Hofer, S., & Frahm, J. (2006). Topography of the human corpus callosum revisited--comprehensive fiber tractography using diffusion tensor magnetic resonance imaging. *Neuroimage, 32*(3), 989-994.

Holtzman, J. D. (1984). Interactions between cortical and subcortical visual areas, evidence from human commissurotomy patients. *Vision Research, 24*, 801-813.

Iacoboni, M., & Zaidel, E. (2004). Interhemispheric visuo-motor integration in humans: the role of the superior parietal cortex. *Neuropsychologia, 42*, 419-425.

Innocenti, G. M. (1980). The primary visual pathway through the corpus callosum: Morphological and functional aspects in the cat. *Archives Italiennes de Biologie, 118*, 124-188.

Iwamura, Y. (2000). Bilateral receptive field neurons and callosal connections in the somatosensory cortex. *Phil Trans R Soc Lond B, 355*, 267-273.

Johansen-Berg, H., Della-Maggiore, V., Behrens, T. E. J., Smith, S. M., & Paus, T. (2007). Integrity of white matter in the corpus callosum correlates with bimanual co-ordination skills. *NeuroImage, 36*, T16-T21.

Kinsbourne, M. (1970). The cerebral basis of lateral asymmetries in attention. *Acta Psychologia, 33*, 193-201.

Koppel, H., & Innocenti, G. M. (1983). Is there a genuine exuberancy of callosal projections in development? A quantitative electron microscopic study in the cat. *Neurosci Lett, 41*(1-2), 33-40.

Lepore, F. (1995). How two becomes one: Functions of the corpus callosum: 1 + 1 = 1, ou comment le corps calleux unifie nos expériences. *Canadian Psychology/Psychologie canadienne, 36*, 278-287.

Lepore, F., & Guillemot, J. P. (1982). Visual receptive field properties of cells innervated through the corpus callosum. *Exp Brain Res, 46*, 413-424.

Lepore, F., Ptito, M., & Guillemot, J. P. (1986). The role of the corpus callosum in midline fusion. In F. Lepore, M. Ptito & H. H. Jasper (Eds.), *Two hemispheres-One brain* (pp. 211-230). New York: Alan Liss.

Manzoni, T., Barabresi, P., Conti, F., & Fabri, M. (1989). The callosal connections of the primary somatosensory cortex and the neural bases of midline fusion. *Exp Brain Res, 76*, 251-266.

Marrocco, R. T., & Li, R. H. (1977). Monkey superior colliculus: Properties of single cells and their afferent inputs. *J Neurophysiol, 40*, 844-860.

Miller, J. (1982). Divided attention: Evidence for coactivation with redundant signals. *Cognitive Psychol, 14*, 247-279.

Miller, J. (2004). Exaggerated redundancy gain in the split brain: A hemispheric coactivation account. *Cognitive Psychol, 49*, 118-154.

Myers, R. E. (1955). Interocular transfer of pattern discrimination in cats following section of crossed optic fibers. *J Comp Physiol Psychol, 48*, 470-473.

Omura, K., Tsukamoto, T., Kotani, Y., Ohgami, Y., Minami, M., & Inoue, Y. (2004). Different mechanisms involved in interhemispheric transfer of visuomotor information. *NeuroReport, 15*(18), 2707-2711.

Poffenberger, A. T. (1912). Reaction time to retinal retinal stimulation with special reference to the time lost in conduction through nervous centers *Archives of Psychology, 23*, 1-73.

Preilowski, B. F. B. (1972). Possible contribution of the anterior forebrain commissures to bilateral motor coordination. *Neuropsychologia, 10*, 267-277.

Ptito, M. (2003). Functions of the corpus callosum as derived from split-chiasm studies in cats. In E. Zaidel & M. Iacoboni (Eds.), *The parallel brain: The cognitive neuroscience of the corpus callosum*. Cambridge: MIT Press.

Raab, D. H. (1962). Statistical facilitation of simple reaction times. *Transactions of the New York Academy of Sciences, 24*, 574-590.

Rakic, P., & Yakovlev, P. I. (1968). Development of the corpus callosum and cavum septi in man. *J Comp Neurol, 132*(1), 45-72.

Reuter-Lorenz, P. A., Nozawa, G., Gazzaniga, M. S., & Hughes, H. C. (1995). Fate of neglected targets: a chronometric analysis of redundant target effects in the bisected brain. *J Exp Psychol Hum Percept Perform, 21*(2), 211-230.

Reuter-Lorenz, P. A., & Stanczak, L. (2000). Differential effects of aging on the functions of the corpus callosum. *Dev Neuropsy, 18*(1), 113-137.

Rosenfeld, W. E., & Roberts, D. W. (2009). Tonic and atonic seizures: What's next-VNS or callosotomy? *Epilepsia, 50 (Suppl. 8)*, 25-30.

Roser, M., & Corballis, M. C. (2002). Interhemispheric neural summation in the split brain with symmetrical and asymmetrical displays. *Neuropsychologia, 40*, 1300-1312.

Savazzi, S., & Marzi, C. A. (2004). The superior colliculus subserves interhemispheric neural summation in both normals and patients with a total section or agenesis of the corpus callosum. *Neuropsychologia, 42*, 1608-1618.

Schiller, P. H., & Logothetis, N. K. (1990). The color-opponent and broad-band channels of the primate visual system. *Trends Neurosci, 13*, 392-398.

Schmahmann, J. D., & Deepak, N. P. (2006). *Fiber pathways of the brain*. Oxford: Oxford University Press.

Sergent, J. (1987). A new look at the human split brain. *Brain, 110*, 1375-1392.

Shorvon, S. D. (2005). *Handbook of epilepsy treatment.* (2nd ed.). Oxford: Blackwell Publishing.

Sperry, R. W. (1986). Consciousness, personality identity, and the divided brain In F. Lepore, M. Ptito & H. H. Jasper (Eds.), *Two hemispheres- one brain: Functions of the corpus callosum* (pp. 3-20). New York: Alan R. Liss.

Tardif, E., & Clarke, S. (2002). Commissural connections of human superior colliculus. *Neuroscience, 111*(2), 363-372.

Tramo, M. J., Baynes, K., Fendrich, R., Mangun, G. R., Phelps, E. A., Reuter-Lorenz, P., et al. (1995). Hemispheric specialization and interhemispheric integration: Insights from experiments with commissurotomy patients. In A. Reeves & D. Roberts (Eds.), *Epilepsy and the corpus callosum 2*. New York: Plenum Press.

Tuller, B., & Kelso, J. A. S. (1989). Environmentally-specified patterns of movement coordination in normal and split-brain subjects. *Exp Brain Res, 75*, 306-316.

Underleider, L. G., & Mishkin, M. (1982). Two cortical visual systems. In M. A. Ingle, M. I. Goodale & R. J. W. Masfield (Eds.), *Analysis of visual behavior* (pp. 549-586). Cambridge: MIT Press.

Van Wagenen, W. P., & Herren, R. Y. (1940). Surgical division of commissural pathways in the corpus callosum. *Arch Neurol Psychiatry, 44*, 740-759.

Wallace, M. T., Meredith, M. A., & Stein, B. E. (1992). Integration of multiple sensory modalities in cat cortex. *Exp Brain Res, 91*, 484-488.

CURRICULUM VITAE- ARTICLES

Ouimet, C., Jolicœur, P., Lassonde, M., Ptito, A., Paggi, A., Foschi, N., Ortenzi, A. & Miller, J. (Accepté). Bimanual crossed-uncrossed difference and asynchrony of normal, anterior- and totally split-brain individuals. *Neuropsychologia.*

Ouimet, C., Jolicœur, P., Miller, J., Ptito, A., Paggi, A., Foschi, N., Ortenzi, A. & Lassonde, M. (2009). Sensory and Motor/Decisional involvement in the Enhanced Redundant Target Effect: a Study Comparing Anterior- and Totally-Split Brain Individuals. *Neuropsychologia, 47*(3), 684-692.

Lassonde, M., et Ouimet, C. (2010). The split-brain. *WIRES Cognitive Science.*

Ouimet, C., Jolicœur, P., Miller, J., Ptito, A., & Lassonde, M. (2007). Enhanced Redundant Target Effect in Callosotomized Individuals is Not Sensory in Nature: Evidence from Total and Partial Split-Brain Individuals. *Visual Cognition- Object Perception, Attention and Memory (OPAM) 2007 Conference Report*.

Arcand, C., Tremblay, E., Vannasing, P., Ouimet, C., Roy, M.-S., Fallaha, N., Lepore, F., Lassonde, M., & McKerral, M. (2007). Development of visual texture segregation during the first year of life: a high-density electrophysiological study. *Exp Brain Res, 180* (2), 263-272.

Ouimet, C. & Jolicœur, P. (2006). The duration of T1 encoding modulates the attentional blink. *Visual Cognition, 15* (3), 290-304.

Lachapelle, J., Ouimet, C., Bach, M., Ptito, A. & McKerral, M. (2004). Texture segregation in traumatic brain injury - a VEP study. *Vision Research, 44*, 2835-2842.